Soil Landscape Restoration of Eroded Hilltops to Improve Crop Productivity over Eroded Landscapes

By

Curtis Graham Cavers

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Department of Soil Science

University of Manitoba

Winnipeg, Manitoba, Canada

Abstract

Soil erosion by tillage has been shown to significantly affect the productivity of agricultural soils of North America. Restoring productivity to these soils requires identification of the problem, quantification of its magnitude and a plan to address the problem effectively. Soil landscape restoration activities were conducted at three sites in south-central Manitoba, in which 15-20 cm of topsoil was removed from depressional areas and added to corresponding hilltops. Measurement and modeling of ^{137}Cs as radioactive tracer data provided quantitative confirmation of continuous, cumulative and unsustainable rates of soil erosion not well explained by pathways of wind or water erosion alone. Soil landscape restoration fully restored ^{137}Cs levels on the hilltops to that in the depressional areas and, depending on the site, at least partially restored soil organic carbon stocks to those in corresponding depressional areas.

The negative effects of soil erosion on crop productivity are difficult to quantify, predict and overcome. Over twelve site-years of field trials in south-central Manitoba, significant, positive biomass responses were observed in two site-years, with significant positive yield responses in four of the twelve site-years. Crop response was influenced by several factors, such as established plant population, crop nutrient (N and P) status, annual effects of weather (growing degree days and precipitation) and available water holding capacity (AWHC) of the soil. Positive crop response was correlated with several factors, including site (Bruxelles), as well as management factors such as long-term no-till, meeting target plant populations and macronutrient (N and P) requirements, adequate growing season precipitation and increases in AWHC from the addition of topsoil to eroded hilltops.

Conducting indoor experiments using constructed soil columns under controlled growing conditions was used to fine-tune treatment responses from field trials with greater precision.

Removing 10 cm of topsoil and adding 10 - 20 cm of topsoil provided the most effective soil landscape restoration strategy. Overall, soil landscape restoration as a soil conservation practice was more effective at some sites than others, but where it was effective, there were increases in soil organic carbon, AWHC and crop yields that would justify the effort in conducting the practice.

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Dedication

This thesis is dedicated to key individuals who have inspired and helped me over the years to reach this milestone: Dr. Tee Boon Goh, Dr. Carl Shaykewich, Prof. Al Ridley, Bob Eilers, Peter Haluschak, Dr. Scott Wright and, of course, Les Henry.

Most of all, thanks be to God through my Lord and Savior Jesus Christ, who made all of this possible, even through pandemics, lockdowns, weather delays, illness, and budget constraints to teach me patience, perseverance, humility, to ask for help when needed and to give credit where credit is due. May this work motivate others to find their purpose, live free and help others.

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Contributions of Authors

The outline of this thesis follows the “grouped manuscript style” whose guidelines are appointed by the Faculty of Graduate and Postdoctoral Studies at University of Manitoba. In accordance with the regulations, the present thesis consists of a collection of manuscripts of which the candidate is the first author. The candidate was fully responsible for the implementation of the studies, supervising research assistants, analysis of data, writing of the manuscripts and responding to reviewer’s comments, and re-submitting the revisions.

Chapter 1 contains an introduction about the study area, research objectives, and thesis contributions; Chapters 2, 3 and 4 are manuscripts, each containing an abstract, introduction, methods, results, discussion, and conclusions; Chapter 5 provides the final synthesis and general conclusions of this research and recommendations for future research.

For Chapters 2, 3 and 4, each study was conceived by Dr. David Lobb and designed by Dr. Lobb and the candidate, Curtis Cavers. The candidate carried out the experiments, collected and analyzed the data. Laboratory sample analyses were performed under the supervision of Dr. Lobb (^{137}Cs) and Dr. Stephen Crittenden (N, P, pH, and EC). Field analysis support was provided by Dr. Sharon Schneider. Statistical analysis support was provided by Dr. Rob Gulden and Dr. Alan Moulin. The three manuscripts were prepared by Curtis Cavers under the supervision of Dr. Lobb and were revised by Dr. Crittenden, Dr. Schneider, Dr. Gulden, and Dr. Moulin. Chapter 1 was published in 2021 in the Agronomy Journal.

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Chapter 1

Introduction and literature review

1.1. Introduction

Globally, the issue of soil erosion, specifically the loss of topsoil, rich in organic matter (SOM), remains the major vehicle for soil degradation (Montanarella et al., 2016; Rojas et al., 2016; Panagos et al., 2019; Brady, 1984) and subsequent loss in crop productivity that is often challenging to measure, prevent and restore. The conundrum is that the loss of topsoil, though significantly impairing crop production in localized areas, is nearly imperceptible to those who farm the land as a whole unless there has been a catastrophic event (Larney et al., 2016). Incremental erosion losses are often masked by agronomic advances, such as the application of fertilizers and irrigation (Rhodes, 2014), use of improved crop varieties (den Biggelaar et al., 2001); and weather-induced year-to-year variability (Shaffer et al., 1994).

It is the loss of organic matter (Kravchenko and Bullock, 2000; Obalum et al., 2017) in these eroded areas that negatively affects crop production from one or more of the following: reduced water holding capacity (Young and Thomson, 2020) and impeded infiltration (NSE-SPRPC, 1981), making it more difficult to withstand periods of drought or excess moisture; reduced soil fertility from a lack of nutrients (Heard, 2019) or a lack of ability to hold nutrients and make them available for crop growth (Murphy, 2014); and undesirable soil structure that is not conducive for seeds to germinate, take root and thrive (Meinen and Robinson, 2020). There may also be biological or microbiological reasons for eroded soil being less favorable to plant establishment and crop growth (Xiao et al., 2017). Eroded soils can result in delayed seedling emergence (Smith, 2008; Lindstrom et al., 1986), variable responses in crop biomass/straw production (Jin et al., 2015; Thelemann et al., 2010; Tanaka, 1995; Lindstrom et al., 1986) and, most importantly, variable but overall reductions in crop yields (den Biggelaar et al., 2001; Weesies et al., 1994;

Battison et al., 1987), depending on the crop, method used in assessing erosion, and the severity of the erosion (Table 1.1).

Table 1. 1. Estimated losses of crop productivity (Mg ha^{-1} cm^{-1} of topsoil) from soil erosion in North America (adapted from den Biggelaar et al., 2001).

Crop	Mean Yields (Mg ha^{-1})	Chernozems (Mollisols)	Luvisols (Alfisols)
Corn	3.3-7.8	-0.08 to 0.189	-0.012 to 1.03
Wheat	1.6-8.0	-0.033 to 0.225	0.015 to 0.143
Soybeans	0.9-2.8	< 0.4 (most soils)	

Other researchers (Schumacher et al., 1994; Gantzer et al., 1990) reported an 8-22% reduction in crop productivity for each 10 cm loss of topsoil under "mild" erosion and a 17-60% reduction under "severely eroded" conditions.

Changes in grain quality (such protein and oil content) are difficult to attribute to erosion. Little research has been done on this relationship to date. Variable responses and differences in grain quality are considered more likely to be influenced by tillage system than compared to erosion (Riley, 2014). Moulin et al. (1994) showed that wheat (*Triticum aestivum*, L.) yields and biomass are generally inversely-related to the degree of soil erosion in a given landscape position, but the interaction of elevation and surface curvature not only influence soil erosion and crop yield, but also factors such as micro-climate, depth to carbonates and salinity. Soil erosion amplifies the challenges of precision management to agricultural landscapes.

It may be difficult, if not impossible, to completely eliminate soil erosion, but it is of paramount importance to reduce it to tolerable levels of less than 10 tonnes ha^{-1} yr^{-1} (5 tons ac^{-1} yr^{-1}) in order to allow soil formation at a rate of 2.5 cm (1 inch) of topsoil every 100-1000 years (Pimentel et al., 1976) to maintain the level of topsoil currently present. Given the rate of soil formation and the rate of erosion, these reductions are cumulative over time (Lobb et al., 2019), in that subsequent erosion events remove additional topsoil and organic matter, further reducing the overall productivity of the soil year after year. The risk is that yields may decline only slightly in the early stages of erosion (when the effects may be reversible) until they reach a critical stage where yields decline drastically (and/or the effects of erosion become irreversible) (den Biggelaar et al., 2001; Hoag, 1998; Pierce et al., 1983). Even reducing or eliminating the amount of tillage, while minimizing further erosion and improving crop yields, does not rapidly rehabilitate eroded areas of the landscape to fully offset the previous damage created by soil erosion (Olson, 2013).

However, den Biggelaar et al. (2001), in their review of soil erosion-crop productivity studies, found examples, such as in OTA (1982), where the majority of the eroded soil (detached and transported particles) is deposited further downslope but within the same landscape. Therefore, this material is conceivably retrievable for restoration purposes. Other researchers have measured the effects of tillage erosion (Lindstrom et al., 1990; Lobb et al., 1995) and demonstrated that soil redistribution within the field landscape is significant and reversible.

The addition of topsoil to eroded hilltops in the Canadian prairies (Smith, 2008; Erb. 2005; Verity and Anderson, 1990) and in the Great Plains of the United States (Papiernik et al., 2009) have demonstrated to varying degrees the potential to replace and restore soil that was re-distributed downslope by tillage, thereby increasing crop productivity almost immediately. Though variable results may depend on depth of topsoil replaced, the biological activity of the replaced topsoil and the amount of compaction sustained in the restoration process, the practice of landscape restoration appears to be a viable, cost-effective, long-term soil conservation practice for restoring eroded landscapes when compared to other alternatives such as irrigation (Dale and Carter, 1955), higher rates of fertilizer (Heard, 2019; Hoag, 1998), amendments such as manure, compost and crop residues (Larney, 2012) or cover crops (Sharma et al., 2018).

1.2. Thesis structure

This thesis is composed of five chapters that address the research objectives:

This chapter, **Chapter 1,** presents a general introduction to soil erosion and provides the research objectives and outline of the thesis. This chapter is followed by three chapters written in the style of scientific journal manuscripts.

Chapter 2 describes changes in soil properties due to practices associated with soil landscape restoration in three select field sites. This chapter seeks to quantify soil erosion losses over time using ^{137}Cs concentrations and inventories and measure changes in soil organic carbon (SOC) concentrations and inventories (stocks) due to landscape restoration practices. In addition, changes in select soil physical properties as affected by soil landscape restoration practices (namely aggregate stability; bulk density, and water infiltration rate/saturated hydraulic conductivity) were evaluated.

Chapter 3 assesses the magnitude of crop response (total biomass and crop yield) at these same three field sites where soil landscape restoration was implemented. Evaluations of factors such as available soil water, nutrients and management factors were conducted to explain the variable responses from each field site, particularly those which could mask changes in crop productivity, including low plant stands, high weed pressure and extremely dry weather conditions.

Chapter 4 examines the crop response to soil landscape restoration in greater detail by removing and adding specific depths of topsoil to constructed columns of soil under controlled growing conditions. This experiment was conducted to develop more detailed recommendations of added and removed topsoil for the most positive outcomes from soil landscape restoration, while looking for any effects based on site (soil characteristics) or crop grown.

Finally, **Chapter 5** summarizes the key findings of this study, the limitations encountered and broader implications of the research, while providing recommendations for further exploration in this field of study.

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Chapter 2

Changes in soil properties due to practices associated with soil landscape restoration

2.1. Abstract

Soil erosion by tillage has been shown in several experiments across North America to significantly affect the productivity of agricultural soils. Restoring productivity to these soils requires identification of the problem, quantification of magnitude of the problem and a plan on how address the problem quickly and effectively. While historical documentation, mapping information and visual cues provide supporting evidence, it is through the measurement and modeling of ^{137}Cs as radioactive tracer data that provide quantitative confirmation of continuous, cumulative and unsustainable rates of soil erosion that are not well explained by pathways of wind or water erosion alone. Despite the amount of academic information pertaining to this topic, adoption of practices to ameliorate tillage erosion continues to be low. To accelerate the return to higher productivity for eroded soils, soil landscape restoration activities were conducted at three sites in south-central Manitoba, in which 15-20 cm of topsoil was removed from depressional areas and added to corresponding hilltop (knoll) areas. Key soil properties were measured by depth and stocks or inventories were calculated. Soil landscape restoration fully restored ^{137}Cs levels in the knolls to that in the depressional areas and, depending on the site, at least partially restored soil organic carbon stocks to those in corresponding depressional areas. Other changes in soil properties (bulk density, hydraulic conductivity, aggregate stability, pH and EC) due to soil landscape restoration activities were of lesser consequence or more site-specific in impact. Further investigation into crop responses will be examined in a subsequent chapter.

2.2. Introduction

The long-term prosperity of civilizations is largely determined by how people treat and manage their soils as a foundation of their food supply (Dale and Carter, 1955). Historically, most civilizations have lasted no more than 1,500 years before their soil resources were exhausted and their food supply collapsed. Agricultural landscapes within the North American Great Plains also are prone to this threat (Halladay, 2020; Lowdermilk, 1953; Ellis,1938), as seen in the dust storms of the Dust Bowl era of the 1930s or gully erosion from major thunderstorms. Because of the sporadic, localized nature of these events, it has been challenging for agricultural producers to focus on the prominence of guarding against soil erosion while other threats to soil and crop productivity, such as salinity, compaction, loss of soil fertility, loss of soil organic matter, abiotic stresses, invasion of pests, etc., need to be addressed. Furthermore, long-term soil management, planning and evaluation is often of secondary importance to the imminent, short-term economic stresses of production agriculture until there is a catastrophic erosion event, such as a wind storm or an intense thunderstorm (Larney et al., 2016), that causes major soil loss and requires either an immediate remedial response or the land in question can no longer be used for food production.

Soil erosion is often difficult to quantify and assess at field scale, because annual losses may appear to be small and go largely undetected, but their overall loss and impact is cumulative (Badreldin and Lobb, 2023). Spatial and temporal variability in productivity within a specific land parcel may be overlooked in years of favorable growing conditions or when larger, more productive areas of the parcel boost the average productivity of the entire parcel (Manitoba Agriculture, 2006). Even though the role of tillage erosion has been well-documented (Van Oost et al., 2006; Lindstrom et al., 2001; Lobb et al., 1995), as a major pathway of soil loss, it is less studied than wind and water erosion events. Recent work by researchers such as Badreldin and Lobb (2023), Thaler et al. (2021)

and Li et al. (2007) show that significant, unsustainable rates of soil loss continue to occur throughout the agricultural regions of North America, and that tillage erosion is a primary force driving this erosion.

Long-term effects of erosion may be masked in the short-term by weather and agronomic factors, such as timely moisture supply (Rhodes, 2014; Hoag, 1998), addition of fertilizer (Kapoor and Shaykewich, 1990; Kenyon, 1988), increasing seeding rates to boost plant stands (Gyssels et al.., 2007), and other agronomic advances (den Biggelaar et al., 2001) can create the illusion of resilient soil productivity. In addition, many of the modern tillage implements currently promoted as conservation tillage tools, such as various configurations of vertical tillage, depending on their operating speed and direction, can be as erosive as moldboard plows or tandem discs, the main tools of historic conventional tillage systems (Lobb, 2008; Lobb et al., 1995). Therefore, a proactive approach to decreasing soil erosion by tillage is needed to avoid critical losses of topsoil, beyond which eroded landscapes will be far more difficult to rehabilitate (Manitoba Agriculture, 2006).

Soil survey maps and reports (the majority of which for Western Canada were produced in the 1930s to 1990s) provide historical, pedological evidence of erosion in parts of the landscape (Anderson and Smith, 2011; Ellis, 1938), but may require specialized training for interpretation and the scale and age of the survey may not be sufficiently detailed to address local variability. For erosion assessments, the interpretations/ratings often suggest the degree of erosion is “minor”, especially when assessed at larger scales (general or reconnaissance levels) that do not isolate sensitive areas where erosion occurs repeatedly over time. Clues are often provided in the descriptions of individual soil series, depicting them as “susceptible to” or “affected by” erosion; their current status will be largely determined by the type of management they have been subjected to since mapping and classification was conducted. In addition, other parts of the landscape may serve as areas of deposition from upslope soil losses, so that topsoil is relocated, but not removed, from the land parcel (Papiernik et al., 2009; Papiernik et al., 2005; De Alba et al., 2004).

In hilly landscapes, soil loss and deposition patterns are not well explained by the pathways of wind and water erosion, and tillage erosion has been shown to be the dominant pathway using radioactive constituents such as ^{137}Cs as tracers to determine in-field soil movement patterns (Fulajtar et al., 2017; Tiessen et al., 2009; Lobb et al., 1995). This method is an effective means of determining the spatial and temporal extent of soil erosion, though not commonly employed beyond research activities. Soil organic matter (SOM), more specifically soil organic carbon (SOC), is a simpler, more accessible measurement of soil productivity (Kravchenko and Bullock, 2000; Gregorich et al., 1994) but is more dynamic in terms of its fates and transformations than conservative tracers, which do not undergo mutual chemical reactions or decay with time (Li et al., 2022). Maintaining soil cover with crop residues, living roots and low soil disturbance tend to decrease erosion by all mechanisms, but do little to hasten the soil formation process over the short term. While great advances have been made to decrease the practice of summerfallow (Agriculture and Agri-Food Canada, 2023) and increase the adoption of no-till practices (Henry, 2024), reductions in soil loss do not suggest an immediate return to the original productivity of eroded soils, because soil formation is an extremely slow process (Pimentel et al., 1976). For this reason, it is important to consider redistributing SOM-rich topsoil rather than trying to increase it in-situ (McGuire, 2023).

The redistribution of soil by tillage erosion must be addressed to restore productivity to areas where topsoil losses have exceeded replacement rates for decades. One potential solution is the practice of physically relocating topsoil from the depositional areas upslope to eroded parts of the landscape has been described as soil landscape restoration (Smith, 2008; Erb, 2005) but also as soil-landscape rehabilitation (Schneider et al., 2021; Papiernik et al., 2009) or topsoil movement or replacement (Schumacher, 2014). Economic payback analyses from earlier soil landscape restoration activities have been shown to be positive (Hacault, 2011; Bosma, 2004).

Soil landscape restoration practices can result in sustained increases in crop productivity, if tillage erosion is minimized. Productivity gains on knolls where topsoil is added are expected to be greater than the losses in corresponding depressions where topsoil was removed for the purpose of landscape restoration (Schneider et al., 2021; Smith, 2008). No yield benefit was observed in a moderately-eroded landscape (Schneider et al., 2021).

Currently, the percentage of producers in Canada who “place eroded soil back on hilltops” is small (nationally from 6% in 2017 to 7% in 2021) and growing only incrementally in the prairie provinces (in Manitoba, from 8% in 2017 to 9% in 2021; in Saskatchewan, from 5% in 2017 to 8% in 2021; and in Alberta, from 4% in 2017 to 7% in 2021) (Statistics Canada, 2023). More information is needed to guide producer adoption of this practice by simplifying the assessment of candidate landscapes and evaluating short- and long-term outcomes in a variety of landscapes and cropping systems.

Many soil quality/soil health factors have links to crop productivity (USDA-NRCS, 2015), but to maximize assessment efficiency while minimizing confounding effects, this study addressed the following objectives: 1) to assess soil erosion losses over time using ^{137}Cs concentrations and inventories; 2) to measure changes in soil organic carbon (SOC) concentrations and inventories (stocks) due to landscape restoration practices; and 3) to evaluate changes in select soil physical properties as affected by soil landscape restoration practices (namely aggregate stability; bulk density, and water infiltration rate/saturated hydraulic conductivity).

2.3. Materials and methods

2.3.1. Site selection and descriptions

Three sites were selected in south-central Manitoba, each possessing an eroded knoll area and an adjacent depression area with variable soil properties and contrasting degrees of crop productivity (Table 2.1). The three sites were selected based on landowner interest in the study and visually observable indicators of erosion, such as exposed subsoil and poor crop stands. All sites have similar annual precipitation, soil temperature, mean air temperature, growing degree days (GDD), and growing season length. Two of the three sites have historical yield data as measurements of long-term productivity differences in the two landscape positions at each site (not reported here), as an indication of in-field variability. The midslope landforms for each site were excluded from the soil sample comparisons to focus on measuring and observing changes in soil properties in the extreme landforms in terms of elevation, slope and slope curvature, the tops and bottoms of hill slopes.

Table 2. 1. General site characteristics of three soil landscape restoration sites (Altamont, Bruxelles and Manitou).

Factor	Site		
	Altamont	Bruxelles	Manitou
Soil Survey Report	D70 (Langman, 1986)	D75 (Langman, 1989)	D77 (Podolsky, 1993)
Municipality	Lorne	Lorne	Pembina
MASC Risk Area	5	5	5
Ecoregion	163	163	156
Ecodistrict	854	854	766
Dominant Soil Order	Dark Gray Chernozemic	Dark Gray Chernozemic	Black Chernozemic
Temperature Class	Cool boreal	Cool boreal	Cool boreal
Moisture Regime	Subhumid	Subhumid	Subhumid
Annual precipitation (mm)	547	547	540
Corn Heat Units	2300 - 2400	2300 - 2400	2300 – 2400
Mean Annual Soil Temp @ 50 cm depth (°C)	2 - 8	2 - 8	5 – 8
Annual snowfall (cm)	136	136	114
Mean July temperature (°C)	19.3	19.3	19.3
Mean January temp (°C)	-17.1	-17.1	-17.5
Length of growing season (days)	182	182	181
Growing Degree Days	1671	1671	1674
Water deficit (mm)	154	154	250
Groundwater table depth (m)	3 - 120	3 - 120	3 - 120
Bedrock	Cretaceous shale	Cretaceous shale	Cretaceous shale
Native vegetation	Aspen - oak (Boreal Forest)	Aspen - oak (Boreal Forest)	Aspen - oak (Boreal Forest)
Elevation (masl)	486 - 489	427 - 457	465 – 472

The experimental design used at all sites was to create four replicates of simple, randomized, paired transects from knoll to depression. “Knoll” was used as a generic term throughout the remainder of this document representing more technically-accurate terms such as hilltops, crests or ridges in undulating to hummocky landscapes. Treatments were either as a control (i.e., unrestored, current treatment), (“control knoll” and “control depression”) or as restored treatment, by which 15 cm topsoil (Altamont) or 20 cm topsoil (Bruxelles and Manitou) was moved from a plot 10 meters square via tractor-drawn earth scrapers from the depression (“removed depression”) and placed in a new plot 10 meters square on the knoll position (“added knoll”). The resulting plot layout was a total of eight (8) plots on the knoll position and eight corresponding plots in the depression position at each site (Figure 2.1). The earth moving equipment used at each site is listed in Table 2.2.

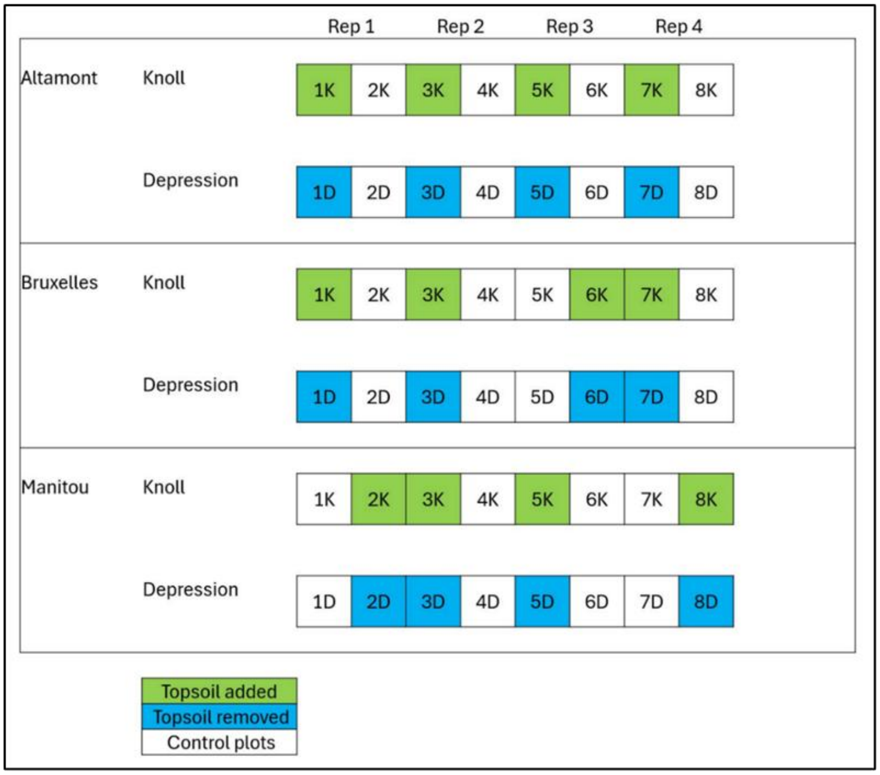

Figure 2. 1. Experimental layout of soil landscape restoration sites (Knoll refers to eroded hilltops).

Table 2. 2. Equipment used for soil landscape restoration at the three sites (Altamont, Bruxelles and Manitou).

Site	Tractor Model (Size)	Scraper Size	Date
Altamont	John Deere 4440 (100 kW)	3 m^3	Oct 8, 2020
Bruxelles	John Deere 9200 (194 kW)	7 m^3	Oct 9, 2020
Manitou	John Deere 8970 (253 kW)	7.7 m^3	Oct 19, 2020

2.3.1.1. Altamont site

The Altamont site (Figure 2.2) is located approximately 13.7 km west of the village of Miami, located in the Rural Municipality of Lorne. The soils that make up this site are relatively young grassland-forest transitional soils prone to encroachment by trees on hummocky topography with slopes 5-9%. Digital elevation maps (1999) place the topography of the site between 486-489 meters above sea level, as confirmed by Langman, (1986). These soils were initially broken up for agricultural purposes during the 1890s and early 1900s (Ellis and Schafer, 1943), although additional land clearing continued well into the 1940s as indicated in various successive orthophotos of specific land parcels. Historical land use for this site has been traditional annual crops (cereals and more recently canola) and trees (Manitoba Land Resource Unit, 1997).

Spatial variability at this site is the main driver of variable crop performance, as influenced by differences in soil moisture and soil fertility between knolls and depressions. This condition is further aggravated over time by evidence of lost topsoil on the knolls moved to downslope areas by tillage (Ellis, 1938). Initial visual inspections of the Altamont site suggest it to be the most severely eroded of the three sites and is still managed under a conventional tillage system with cultivators, chisel plows and sweeps on the seeding equipment (see Table 2.3). Under periods of high precipitation, sidehill seeps of groundwater were observed that created an excess water condition in the depression plots that limited accessibility and timely field operations. The presence of stones did not result in a downgrading of the agriculture capability rating at the time of the soil survey, but the number and size of stones present may adversely affect some present-day field operations, and the movement of stones by tillage operations has resulted in the accumulation of stones in concave landforms throughout this field.

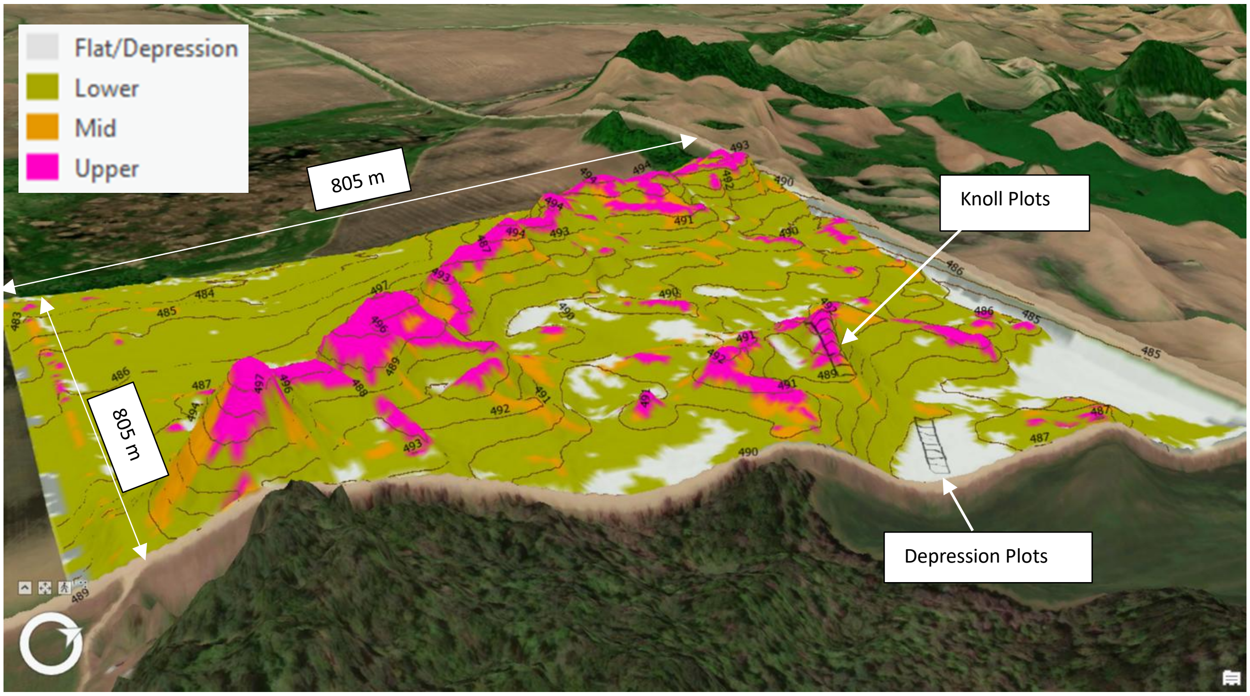

Figure 2. 2. Landform classes at Altamont site and their relative area of the highlighted parcel (total area approximately 65 ha). Vertical exaggeration 10x.

Table 2. 3. Field operations at the three soil landscape restoration sites (2021-2023).

Year	Location	Tillage System	Fall Tillage	Spring Tillage	Preceding Crop	Crop Type (Variety)	Seeding Date	Seeding Equipment	Fertilizer (actual N-P-K-S, kg/ha)
2021	Altamont	Conventional	Chisel Plow	Harrow after seeding	Soybean	Wheat (Cardale)	May 13	Harmon air seeder (sweeps)	100-40-0-0
	Bruxelles	No-Till	Heavy Harrow	None	Canola	Wheat (AAC Brandon)	April 26	Bourgault	80-30-0-0 MRB on knolls 115-30-0-0 MRB in depressions
	Manitou	No-Till	Heavy Harrow	None	Wheat	Canola	May 13 June 1 re-seed	John Deere 1895	130-40-0-85 MRB
2022	Altamont	Conventional	Chisel Plow	Fertilizer Broadcast Harrow 2X	Wheat	Canola (Pioneer 45CS39)	May 27	Harmon air seeder (knives)	110-0-0-25 BC 0-45-0-0 SP
	Bruxelles	No-Till	Heavy Harrow	None	Wheat	Oat (3245)	May 24	Bourgault	75-0-0-0 MRB on knolls; 110-0-0-0 MRB in depressions
	Manitou	No-Till	Heavy Harrow	None	Canola	Soybean (Liska)	May 23	John Deere 1895	Peat inoculant 75 lb/ac as 11-52-0 SP
2023	Altamont	Conventional	Chisel Plow	Fertilizer Broadcast Harrow 2X	Canola	Wheat (Starbuck)	May 23	Harmon (sweeps)	80-0-0-20 BC 0-45-25-0 SP
	Bruxelles	No-Till	Heavy Harrow	None	Oat	Canola (L340)	May 21	Bourgault	110-35-0-21 MRB
	Manitou	No-Till	Heavy Harrow	None	Soybean	Wheat (AAC Brandon)	May 10	John Deere 1895	95-36-0-0 MRB

BC = broadcast; MRB = midrow band; SP = seed-placed

2.3.1.2. Bruxelles site

The Bruxelles site (Figure 2.3) is situated 3.2 km west and 1.6 km south of the south junction of Provincial Road 245 and Provincial Trunk Highway 34, approximately 17.6 km northwest of the village of Somerset, located in the Rural Municipality of Lorne. The Bruxelles site is also severely eroded, similar to Altamont, but has been managed under a no-till management system since circa 2004, longer than the other two sites. Bruxelles is the only site where there is a potential change in surface texture resulting from soil landscape restoration because topsoil from a Dezwood clay loam was placed on top of an eroded Vandal loam over sand. Concerns raised by Smith (2008) regarding mixing different soil textures did not occur at Bruxelles because the texture of Dezwood changes very little with depth and subsequent topsoil removal. The addition of clay loam topsoil to a lighter-textured soil on the knoll should not result in any negative outcomes due to the possible addition of clay particles.

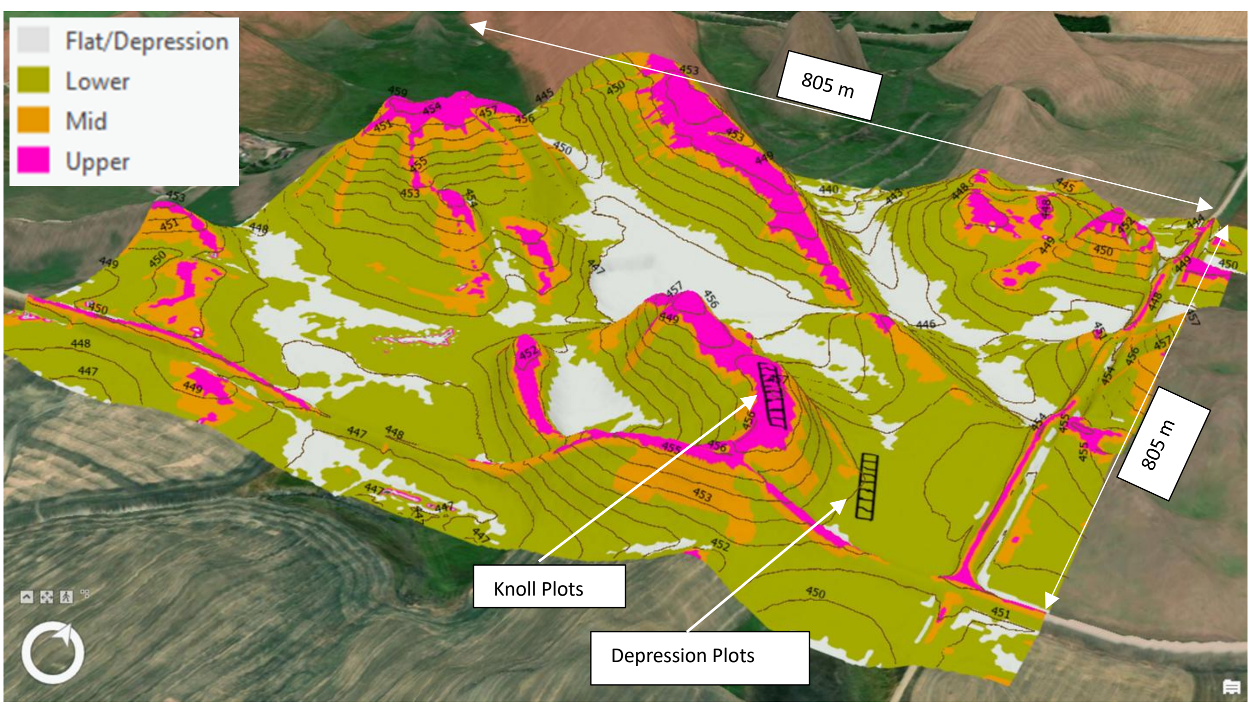

Figure 2. 3. Landform classes at Bruxelles site and their relative area of the highlighted parcel (total area approximately 65 ha). Vertical exaggeration 10x.

2.3.1.3. Manitou site

The Manitou site is situated 4.8 km west of the village of Manitou and approximately 2.4 km south on Road 51 West., located in the Rural Municipality of Pembina. The Manitou site is more moderately eroded than the other two sites and has been managed under a no-till system since 2019. Surface drainage improvements in the depression area have resulted in occasional presence of a shallow water table and slightly saline conditions. Boulders are found on this site but are rare and tend to be found in clusters. Low pH values found at this site are generally rare in Manitoba, but the shale bedrock at this site has little to no carbonates present.

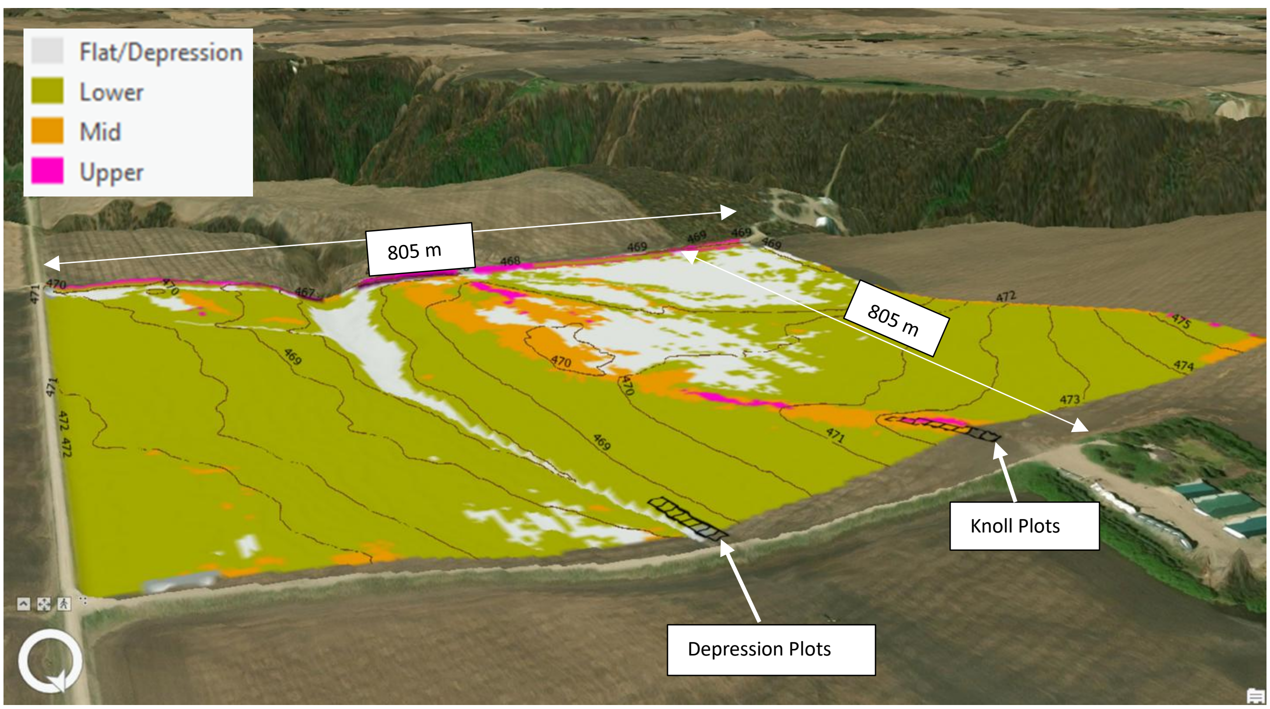

Figure 2. 4. Landform classes at Manitou site and their relative area of the highlighted parcel (total area approximately 65 ha). Vertical exaggeration 10x.

2.3.2. Soil properties summary

A summary of the relevant pedological information for the three sites is provided in Table 2.4. All sites compared two extreme landscape positions with measurable differences in water limitations (droughtiness versus excess) and water redistribution within the landscape (runoff versus ponding or percolation).

Five of the six soil series (excluding Guerra, the soil series at the Manitou depression) possess either a Bt or Btj horizon, indicative of an accumulation of clay particles from above leached horizons. Two of these soil series (Poyser and Dezwood, found at the Altamont knoll and the Bruxelles depression, respectively) express a thin Ae horizon indicative of significant leaching of clay and carbonates over time. Even though no Ae is reported for Tellier (the soil series at the Altamont depression), Vandal (the soil series at the Bruxelles knoll) and Fifere series, it is plausible that an Ae horizon may have been present at one time, either discontinuous in spatial presence or assimilated into the Ah horizon over time by tillage. Only the Dezwood series is reported to have an accumulation of carbonates at depth in the form of a Cca horizon. Only the Guerra series is reported as a poorly drained depression. These same five soil series (excluding Guerra) suggest native vegetation was either forest or a forest-grassland transition area where leaching of constituents and the accumulation of biomass above-ground were the dominant soil-forming processes prior to cultivation for agriculture.

LIDAR elevation data at 1-m resolution (ArcGIS) was analyzed for elevation, slope, slope curvature, landform classification and aerial extent of landform using the concept of geomorphologic phenotypes (MacMillan and Shary, 2009) to classify into one of four general landform categories: upslope, midslope, lower slope and depression. These categories are summarized in Figures 2.2 – 2.4 as an approximation of the aerial extent of the “knoll” or upslope portion of the landscape in comparison to the “depression” or lower slope portion of the landscape at each site, representing the two extreme landscape features of each land parcel that are under the same crop production management system.

Table 2. 4. Soil series characteristics by site.

Site	Altamont		Bruxelles		Manitou	
Position	Knoll	Depression	Knoll	Depression	Knoll	Depression
Soil Series[1]	Poyser	Tellier	Vandal	Dezwood	Fifere	Guerra
Info Source	D70	D70	D75	D75	D77	D77
CSSS Classification[2]	Orthic Gray Luvisol	Gleyed Dark Gray Chernozem	Orthic Dark Gray Chernozem	Orthic Dark Gray Chernozem	Orthic Dark Gray Chernozem	Rego Humic Gleysol
Map Scale	1:50 000	1:50 000	1:20 000	1:20 000	1:50 000	1:50 000
Texture	Clay loam	Clay loam over loam	Loam over gravelly sand	Clay loam	Loam	Loam over silty clay loam
Internal Drainage	Well	Imperfect	Rapid	Well	Well	Poor (with surface drainage)
Agriculture Capability	2T	2W	3MT	2X	2T	5W (3W with surface drainage)
Salinity	No	No	No	No	No	Sometimes Slightly
Calcareous	Moderate to strong	Moderate to strong	Moderate to strong	Moderate to strong	Weak to neutral	Moderate to strong
Parent Material	Mixed till	Mixed till	Glacio-fluvial	Mixed till	Shale till	Mixed till
Solum depth	50 cm	45 cm	45 cm	40 cm	70 cm	25 cm
	Ap/Ah (10-20 cm)	Ap/Ah (10-20 cm)	Ap/Ah (10-18 cm)	Ah/Ap (15-20 cm)	Ap/Ah (15-18 cm)	Ah/Ahk (15-30 cm)
	Ae (5-10 cm)	Ae (?)	Ae (?)	Ae (2-4 cm)	Ae (?)	AC (5-15 cm)
	AB (10-15 cm)	Bt/Btj (20-30 cm)	Bt/Btj (20-35 cm)	Bt (20-40 cm)	Bt (25-35 cm)	
	Bt (15-20 cm)	II BC (10-15 cm)		Cca (15-30 cm)	BC (10-30 cm)	
	Ck	II Ck	II Ck	Ck	C	Ck
Water Holding Capacity	Medium	Medium	Low	Medium	Low	Medium
Other Notes	Moderately eroded		Moderately eroded		Subject to erosion	
Slope	5-9%	0-0.5%	9-15%	2-5%	2-5%	0-0.5%
Dominant Slope Curvature Class[3]	Plan = convex Profile= convex	Plan = plane Profile= plane	Plan = convex Profile = convex	Variable	Variable	Plan = plane Profile = concave
Landform Classification[3]	Upper slope	Flat; depression	Upper slope	Lower slope	Upper slope	Lower slope
% of Landbase[3]	15	12	9	35	10	82

[1]Soil series in a natural, uncropped state

[2]Canadian System of Soil Classification (Expert Committee on Soil Survey, 1982)

[3]LIDAR/Geomorphologic data

Historical aerial photographs were accessed via the Earth Observation Data Management System (EODMS), National Air Photo Library, Natural Resources Canada, as a supplementary means to assess changes in soil erosion over time. Common years in which all three sites were photographed were selected for ease of comparison. Recent aerial photos were retrieved from satellite imagery (Google Earth®) to continue documentation of the trends in land use and signs of erosion. Visual inspection of aerial photography over time (Figures 2.5 – 2.7) suggests an increase in erosion from 1958 to 1980 which may have slowed from 1980 to 2023 due to conservation efforts, but erosion has not ceased or been reversed.

Figure 2. 5. Aerial photos of the Altamont site: a) 1958 and b) 1980 (EODMS); c) 2023 (Google Earth). Lighter-coloured borders of red areas indicate eroded knolls; darker-coloured borders indicate depressions.

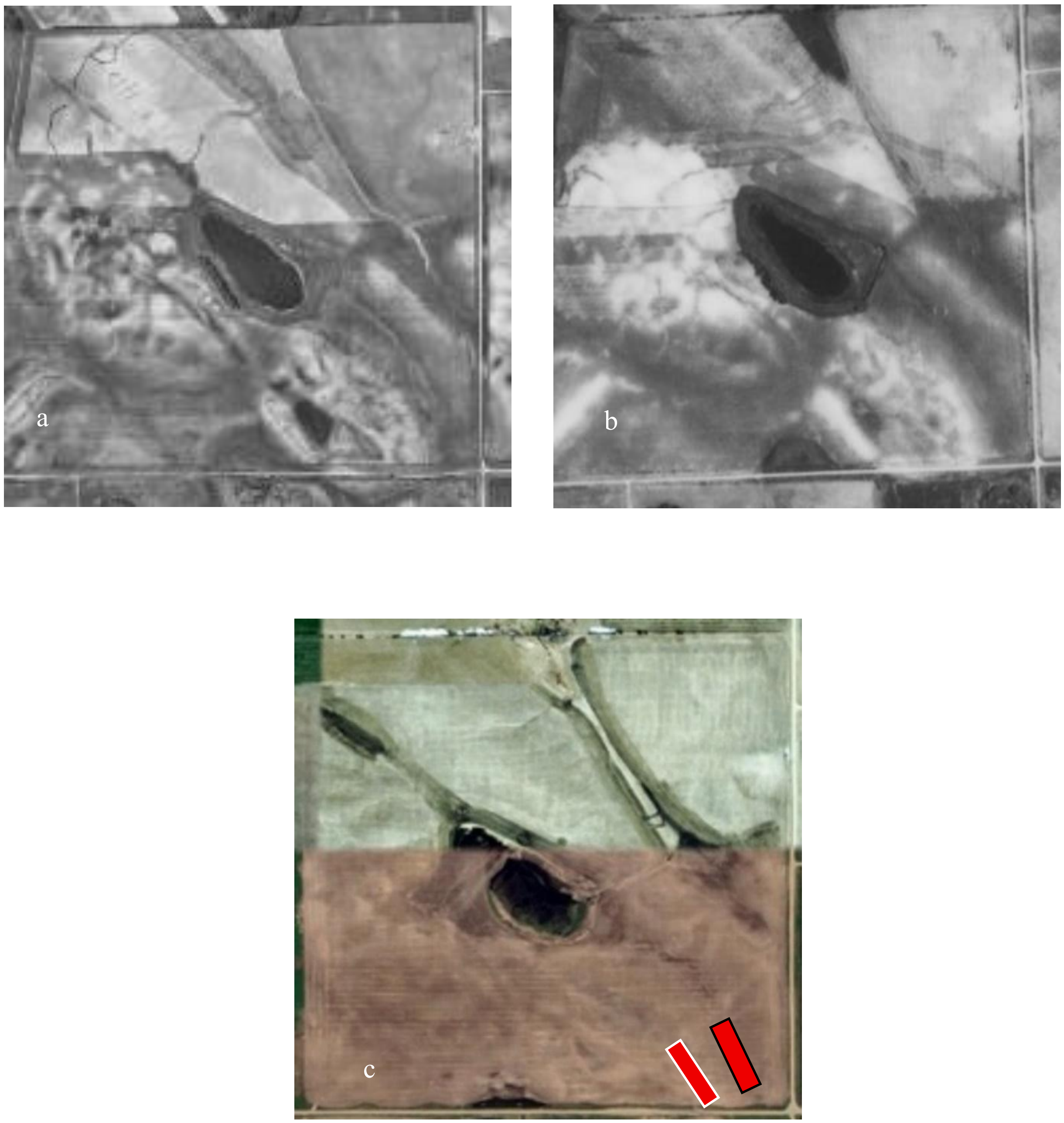

Figure 2. 6. Aerial photos of the Bruxelles site: a) 1958 and b) 1980 (EODMS); c) 2023 (Google Earth). Lighter-coloured borders of red areas indicate eroded knolls; darker-coloured borders indicate depressions.

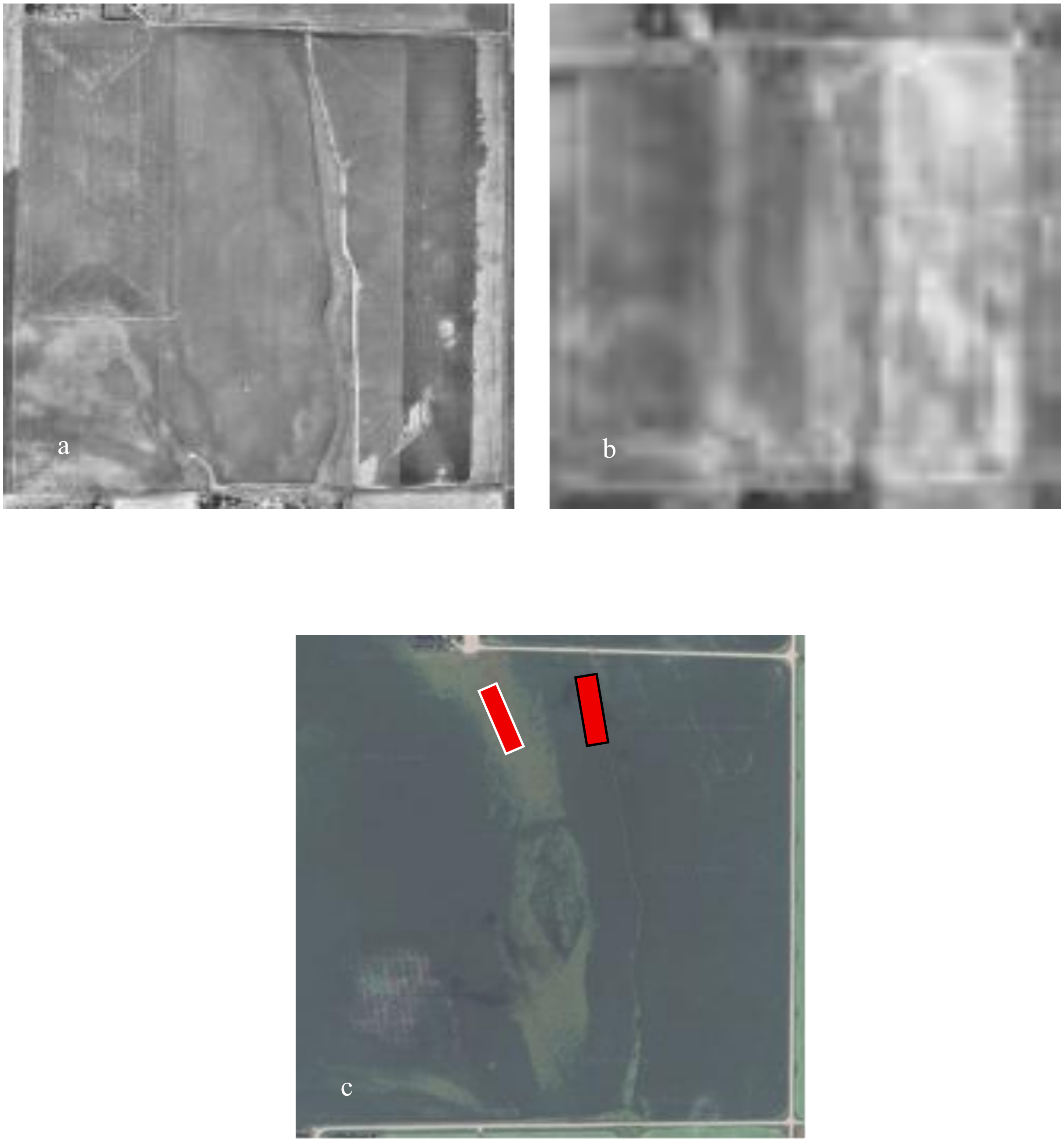

Figure 2. 7. Aerial photos of the Manitou site: a) 1958 and b) 1980 (EODMS); c) 2023 (Google Earth). Lighter-coloured borders of red areas indicate eroded knolls; darker-coloured borders indicate depressions.

2.3.3. Soil sampling for physical and chemical properties

Fall soil samples were collected after each harvest from 2020 to 2023 using a 38-mm diameter soil core sampler for consistency at all depths. Repeated fall sampling was conducted to ensure enough samples for temporal analysis, if necessary, and for analysis of variance among sites, landscape positions and treatments. Samples were collected as one composite sample from three cores per plot, at 0-5, 5-15, 15-30, 30-60 and 60-90 cm depths.

Soil pH and soil electrical conductivity (EC) were determined using a 1:2 soil to water ratio (McKeague, 1978). Total carbon (TC) analysis was determined by combustion method (Nelson and Sommers. 1996) at 900ºC. Inorganic carbon (IC) analysis was determined by the modified pressure-calcimeter method (Sherrod et al., 2002). Soil organic carbon (SOC) values were determined by difference of total carbon and inorganic carbon. Bulk density values were collected in the fall of 2023, dried and weighed for a cursory assessment of soil compaction, but, more importantly, for converting concentrations of various constituents over a range of depths into single-value stocks or inventories for more direct comparisons. Sampling for the relative fraction of water-stable aggregates in the 0-15 cm depth was conducted in 2021 using a wet sieving apparatus (Royal Eijkelkamp, 2022). Samples of sieved, air-dried aggregates between 1- to 2-mm diameter were pre-moistened and wet sieved through a 60-mesh (0.25 mm) screen for 3 minutes in compliance with Kemper and Rosenau (1986) methodology.

Hydraulic conductivity measurements of the soil surface layers were conducted in fall of 2022 and 2023 using a 10-cm diameter pressure infiltrometer attachment assembly (part number 2805D20, Soil Moisture Equipment Corp) to a Guelph Permeameter® measuring stabilized infiltration rates at approximately 30 minutes after the addition of water at 10 cm head.

2.3.4. ^{137}Cs analyses

Soil sample collection and analyses occurred in fall, 2020, at the initiation of landscape restoration activities, post-harvest using a truck-mounted, hydraulic soil sampling unit with a probe with a core diameter of 38 mm and a sampling depth up to 90 cm using five standardized sample depth intervals throughout the study (0-5, 5-15, 15-30, 30-60 and 60-90 cm). Surface (0-5 cm) samples were supplemented using a shovel of known area to ensure adequate sample for analysis. These samples were used for ^{137}Cs analysis in 2020 using the methodologies described by Fulajtar et al. (2017) and Walling and Quine (1993), performing gamma-ray spectrometry in the laboratory by using standard and low-background high-purity Germanium gamma detectors including Broad Energy detectors (BE6530) and a high-resolution Small Anode Germanium (SAGe) well detector (GSW275L) (Mirion Technologies, Canberra, Australia Inc., Meriden, CT, USA) at the Landscape Dynamics Laboratory, University of Manitoba, Winnipeg, Canada. The spectra were analyzed with Canberra Genie 2000 software. The activity of ^{137}Cs in the samples were derived from the gamma-ray energy lines at 661.6 keV (Lobb et al., 1995).

The above field sampling process, described in Lobb et al. (1995) had samples prepared for laboratory analysis in the same manner as described in Zarrinabadi (2024). In this study, data was decay-corrected to January 1, 2020, and reference values for these sites were determined to be 1500 Bq m^{-2} (Li et al., 2008). Calibration for the fallout radionuclides was conducted by the measurement of the mixed radionuclide reference material IAEA-447 (Shakhashiro et al., 2012).

2.3.5. Estimation of rates of erosion and deposition using Mass Balance Model-2

Using ^{137}Cs inventories from the control plots on the knolls and in the depressions, the Mass Balance Model-2 (MBM2), also known as the “Power Model”, was selected as the model to simulate erosion and deposition rates (Mg ha^{-1} yr^{-1}) on these three sites based on the degree of reduction in the ^{137}Cs inventory relative to the ^{137}Cs reference inventory derived from an off-site

^{137}Cs reference level. Similarly, the degree of enrichment of the ^{137}Cs inventory relative to the ^{137}Cs reference inventory provides an estimate of the deposition of topsoil in areas of accumulation, but model limitations may result in deposition rates that are underestimated (Lobb and Kachanoski, 1997; Li et al., 2010; Walling et al., 2011; Zhang et al., 2018). Compared to other models, MBM2 is a conservative but reasonably accurate estimator of erosion rates (Hassouni and Bouhlassa, 2006; Walling and He, 2001). According to Zapata (2003), the total ^{137}Cs inventory A(t) is:

$$\blacktriangle A/\blacktriangle t = (1-\Gamma)I(t)-(\lambda+PR/D)A(t)$$

Where A(t) is ^{137}Cs activity (Bq m^{-2}); R is the erosion rate (kg m^{-2} yr^{-1}); D is the average mass depth (kg m^{-2}); λ is the decay constant for ^{137}Cs (yr^{-1}); I(t) is the annual ^{137}Cs deposition rate (Bq m^{-2} yr^{-1}); Γ is the proportion of the recently deposited ^{137}Cs fallout eliminated by erosion before being mixed into the plow layer; P is the particle size factor. In this determination, the values used were: 20 cm for the average tillage depth; 30.02 yr^{-1} for the decay constant for ^{137}Cs (Leblond, 2024); annual ^{137}Cs deposition rates were pre-set in software; 0.75 for the proportion of recently deposited ^{137}Cs fallout eliminated by erosion before being mixed into the plow layer; and 1.0 for the particle size factor (due to the non-sorting process of tillage erosion). Start year of cultivation was set at 1960 (Zarrinabadi, 2024), giving an approximate time period of 60 years for erosion to occur.

2.3.6. Statistical analyses

Analysis of Variance (ANOVA) was conducted to compare landscape restoration treatments in ^{137}Cs inventories, inorganic and organic carbon concentrations and stocks, using the Glimmix procedure (SAS version 9.4, SAS Institute, Cary, NC) with log-normal (concentrations), and Gaussian (inventories and stocks) distributions. The effect of landscape restoration (topsoil removal or addition) was considered a fixed effect, while the site-years and replicates were considered as random effects in the ANOVA. Mean separation between treatments was determined using the Tukey-Kramer test with a probability level for significance of 0.05. Normality of the residuals and homogenous variances in the ANOVA were tested using Proc Univariate procedure (i.e., Shapiro-Wilk test) and accounted for using Proc Glimmix. The SAS Glimmix model is a generalized linear mixed model based analysis that uses ANOVA and accommodates non-normal data that may also have unequal variances (Stroup, 2015).

Boxplots were used to present the data in the majority of the figures to provide a visual representation of medians, ranges (25th and 75th percentiles) and outliers amongst groups. Figures depicting boxplots were generated in R® to summarize the distribution of continuous variables using the median, quartiles and interquartile range, with whiskers and individually plotted outliers indicating data spread and extreme values amongst groups (version 4.0.1, R Core team, 2020).

Summary statistics were compiled for ^{137}Cs concentrations, soil bulk density, weighted water-stable aggregates and saturated hydraulic conductivity rates were calculated and analyzed using R (version 4.0.1, R Core team, 2020) and SAS (SAS® OnDemand for Academics, SAS Institute Inc. 2024-2025). Soil pH values were analyzed to determine any significant differences among sites or treatments; EC values were assessed to confirm whether threshold values >2000 µS cm^{-1} were exceeded.

2.4. Results and discussion

The degree of erosion measured at the three sites was assessed using ^{137}Cs analysis to rank the three sites and estimate soil erosion rates over approximately the last sixty years. Soil carbon, bulk density, aggregate stability and hydraulic conductivity, along with soil pH and EC, are presented to give an overall assessment of the three sites and their treatments in addition to the background information from the methods section.

2.4.1. ^{137}Cs concentrations and inventories

^{137}Cs concentration profiles (Bq kg^{-1}) for treatments/landscape positions at Altamont, MB are reported using the midpoint for each depth interval in Figure 2.8. In general, ^{137}Cs levels drop off to non-detectable concentrations at depths beyond 15-30 cm (22.5 cm midpoint). In the depression treatments, ^{137}Cs levels decline more rapidly with depth after 15 cm of topsoil was removed. This means the bulk of the ^{137}Cs is associated with the near-surface depths of the soil profile, and the removal of topsoil, either through mechanical transport or via erosion processes, is reflected in the reduced ^{137}Cs concentrations. Conversely, ^{137}Cs concentrations for the added knoll treatment are consistenly higher and deeper into the profile than in the control knoll treatement. Similar trends were observed in the other two sites (Appendix Figures A1 and A2).

When ^{137}Cs concentrations were used to calculate single-value ^{137}Cs inventories ("stocks") for each plot, to evaluate differences among landscape positions, treatments and sites become more apparent (Figure 2.9). There was no significant difference in ^{137}Cs inventories among sites *(P* = 0.6141); across all sites, significant treatment differences ($P < 0.0001$) indicated removing topsoil from depressions reduced ^{137}Cs inventories from corresponding control treatments, but not significantly. However, adding topsoil to eroded knolls significantly increased ^{137}Cs inventory values to mimic those found in the depressional areas.

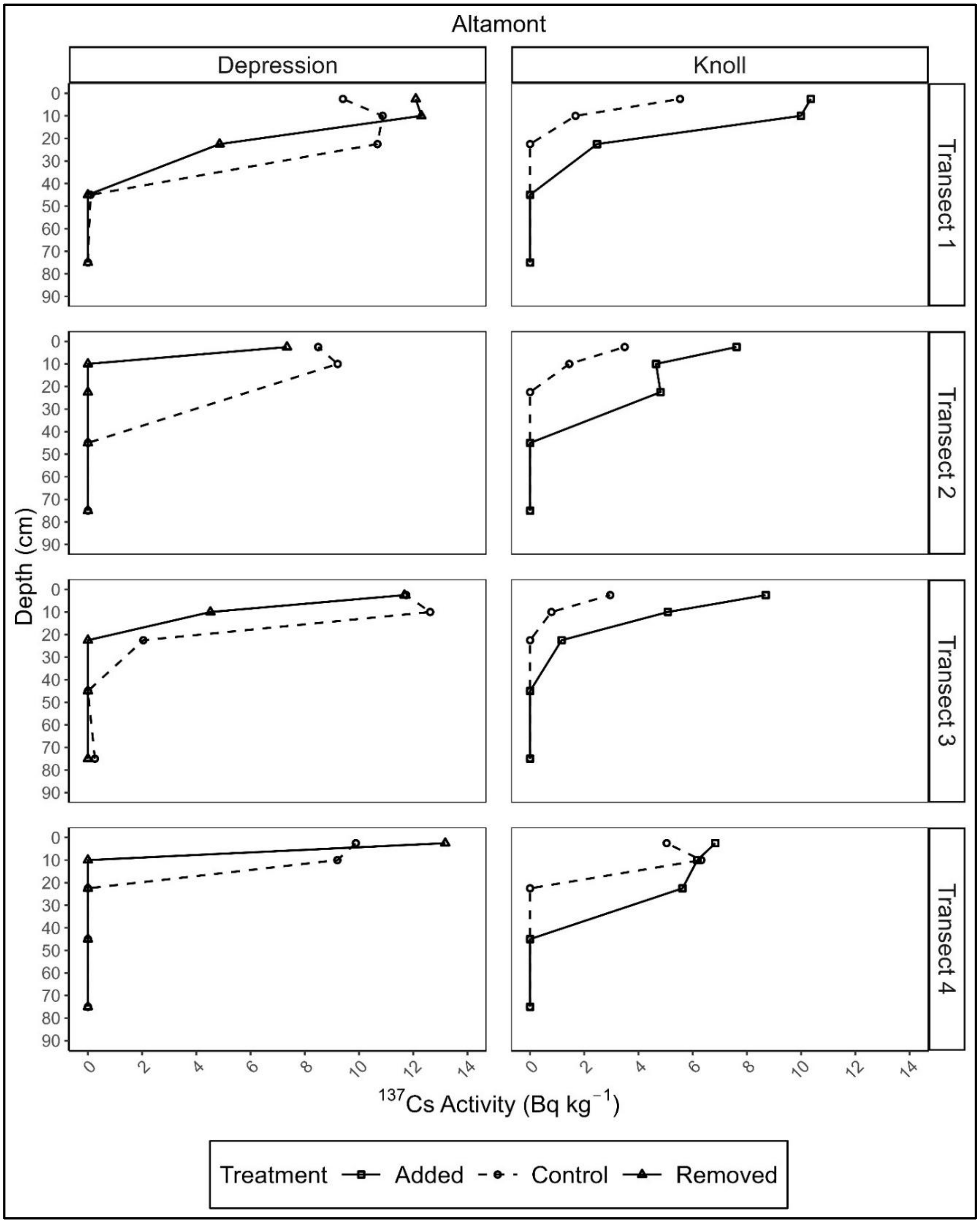

Figure 2. 8. ^{137}Cs concentration profiles (Bq kg^{-1}) for treatments/landscape positions at Altamont, MB. Added refers to 15 cm topsoil added to knoll; removed refers to 15 cm topsoil removed from depression. Control is untreated conditions prior to topsoil movement for landscape restoration.

^{137}Cs inventories at the control knoll for all sites were approximately 44-56% of the 1500 Bq m^{-2} reference level, indicative of substantial erosion over the last 60 years, with the degree of topsoil removed greatest at the Altamont site and least at the Manitou site. (Table 2.5). Conversely, deposition in the control depressions based on ^{137}Cs inventories were approximately 1.6 – 1.9× greater than reference levels, indicating considerable topsoil deposition, though not necessarily solely from the knoll positions that were measured, had taken place in these depressions over the last 60 years, with the degree of deposition also greatest at Altamont and least at Manitou.

The loss of topsoil from the knolls and the deposition of topsoil in the depressions indicates that much of the topsoil removed from the knolls was not lost permanently; rather, it was redistributed within the field landscape, an indicator that tillage erosion was the dominant erosive mode of action. Furthermore, when comparing the effects of removing topsoil from depressions and adding topsoil to knolls using ^{137}Cs inventories, it becomes apparent that adding 15-20 cm of topsoil to eroded knolls reverses the effects of tillage erosion since circa 1960.

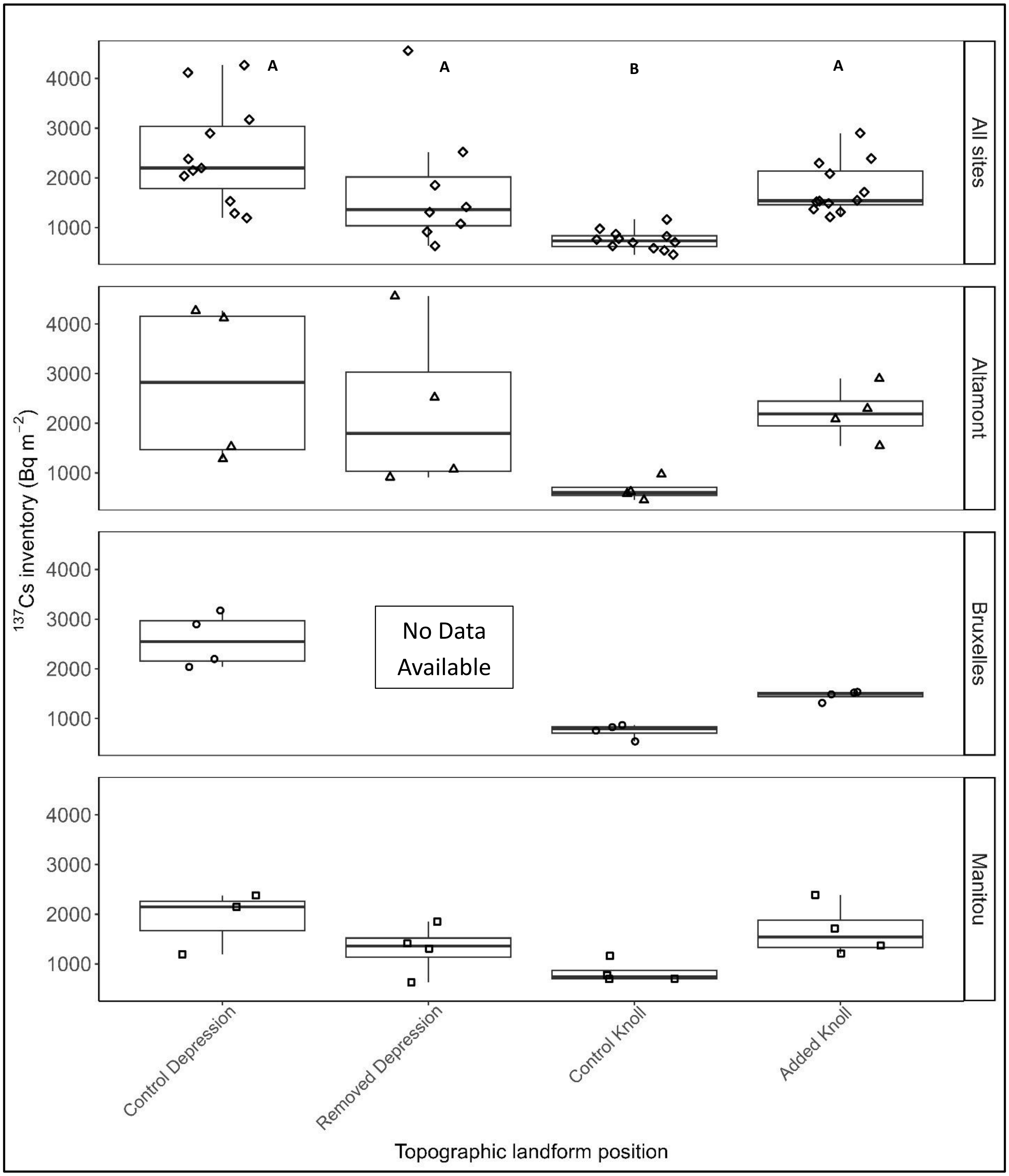

Figure 2. 9. Boxplot distribution of ^{137}Cs inventories (Bq m^{-2}) by topographic landform position and treatment: i) All sites; ii) Altamont; iii) Bruxelles; and iv) Manitou. Significant treatment effect ($P <$ 0.0001); site effect ($P = 0.6141$) and site × treatment interaction ($P = 0.8422$) were non-significant. Boxplots for all sites combined superseded by different letters are significantly different based on Tukey Kramer means separation at $\alpha = 0.05$

Table 2. 5. Calculated annual erosion/deposition rates (Mg ha^{-1} yr^{-1}) using ^{137}Cs data and Mass Balance Model-2 (MBM-2) by site and transect (unrestored (control) treatments).

Site	Landscape Position	Cs-based soil erosion rates (Mg ha^{-1} yr^{-1})				
		Transect 1	Transect 2	Transect 3	Transect 4	Mean
Altamont	Knoll	21.3 (626)*	23.1 (583)	29.5 (453)	10.4 (974)	21.1
	Depression	-66.8 (4269)	3.7 (1283)	-73.2 (4118)	-0.6 (1530)	-34.2
Bruxelles	Knoll	13.2 (867)	14.4 (824)	16.6 (756)	25.1 (537)	17.3
	Depression	-28.8 (2896)	-14.7 (2197)	-11.8 (2036)	-43.3 (3173)	-24.7
Manitou	Knoll	6.1 (1162)	18.4 (703)	16.0 (774)	18.6 (696)	14.8
	Depression	-11.5 (2148)	-20.1 (2379)	5.5 (595)	-9.3 (1907)	-8.9

* ^{137}Cs inventory values in parentheses; reference value used = 1500 Bq m^{-2}

2.4.2. Rates of soil erosion modeled with MBM-2 and Cs data

Table 2.5 examines the modeled estimation of annual soil loss and deposition rates based on the ^{137}Cs inventories for each site. Assuming consistent, cumulative and linear soil losses over time, soil losses of 15 – 20 Mg ha^{-1} yr^{-1} suggests 68 – 90 mm (7-9 cm) of topsoil has been removed from the knoll positions over the past 60 years. Schneider et al. (2021), using the WaTEM to estimate erosion losses over the past 60 years, modeled a net erosion loss of 40 Mg ha^{-1} yr^{-1} on what was considered a moderately-eroded site in South Dakota and a net loss of 130 Mg ha^{-1} yr^{-1} on a severely-eroded site in Minnesota. Average erosion losses of 2 mm year^{-1} for the US Corn Belt using high-resolution topographic surveys are reported in Thaler et al. (2022) and Thaler et al. (2021), but their estimates account for the entire time since cultivation (over the past 150 years).

Based on the solum depths reported in Table 2.4 (from 1986 to 1993, depending on which soil survey report, which would have measured the depth of solum approximately 26-33 years after ^{137}Cs deposition) it was estimated that 35-90% (3.5 – 4.5 cm) of the topsoil in cultivated Ap horizons were removed by these erosion rates over a 30-year time period, though this was difficult to measure, as consistent tillage depths mix subsurface material into the Ap horizon following topsoil removal. Whether recent conservation efforts by the producer landowners (no-till at Bruxelles and Manitou) have slowed erosion rates was not determined. Soil properties at the Manitou site (Table 2.4) suggest erosion may be less severe than at the other two sites (as confirmed in Table 2.5). However, all soil series at the knoll positions were described as either "moderately eroded" or "subject to erosion" in their respective soil survey reports (Table 2.4). Zhang et al. (2021), in a summary of 290 worldwide experiments on topsoil removal and crop yields, determined crop effects from erosion are only significant for corrective action if the current thickness of the A horizon is less than 25 cm and the depth of topsoil eroded away was greater than 5 cm (i.e., a 20% loss on soils with less than 25 cm of topsoil present). Based on these criteria, the soil types on the knolls at all three sites would qualify for corrective action and have a positive crop response. The corresponding depression areas measured at each site indicated measurable rates of soil deposition received from upslope positions, which may include areas other than those measured, based on tillage direction and distance between these landforms. Some of the depression areas may have been subject to water erosion losses, resulting in lower net deposition rates over this time period (not measured).

The Altamont site had the highest mean rate of erosion based on the MBM-2 model. Mean erosion rates on the knoll were classified as moderate (11-22 Mg ha^{-1} yr^{-1}) (Badreldin and Lobb, 2023), with deposition rates in the depression ranging from very high to a low rate of erosion. The mean rate of deposition was greater than the corresponding mean rate of erosion, suggesting additional erosion from multiple locations within the landscape have been translocated into the depression area. This would be influenced by the type, speed and direction of tillage operations conducted over the long term and the slope complexity of the depression area at this site.

The Bruxelles site had the second-highest mean rate of erosion but with more consistent, lower rates of deposition than measured at Altamont. Bruxelles also had a mean rate of deposition greater than the mean rate of erosion, indicating material from other parts of the landscape, outside of the study area, was translocated downslope to the depression area.

The Manitou site was less eroded than the other two sites, with lower mean deposition rates than the other sites and even a low rate of erosion in the depression of one of the transects. Mean rate of erosion was higher than mean rate of deposition, which means either translocated soil did not fully reach the depositional area, which may be the case, as the distance between the two landscape positions is greater than those at the other two sites, or some of the soil deposited in the depression was removed by water erosion beyond the study area.

Relatively small portions of the landscapes at each of the three sites were subject to significant, unsustainable rates of soil erosion (Figures 2.2 – 2.4); however, with much of the soil deposition occurring downslope and within field boundaries, net soil loss was much more subdued when the entire field was considered. A whole-field or regional assessment of erosion may provide a skewed perspective, as the upper slopes continue to lose topsoil and subsequent productivity over time, until a critical point is reached when subsoil is moved downslope and covers the topsoil on other landscape positions, negatively impacting productivity in the lower-slope areas of the landscape (Lobb, 2011).

2.4.3. Soil carbon

Total carbon concentrations (the sum of organic and inorganic carbon, expressed as $g\ kg^{-1}$) was measured across all site-years (including 2020) and treatments by depth and depicted individually in Figure 2.10. Removing topsoil from the depression significantly lowered organic carbon

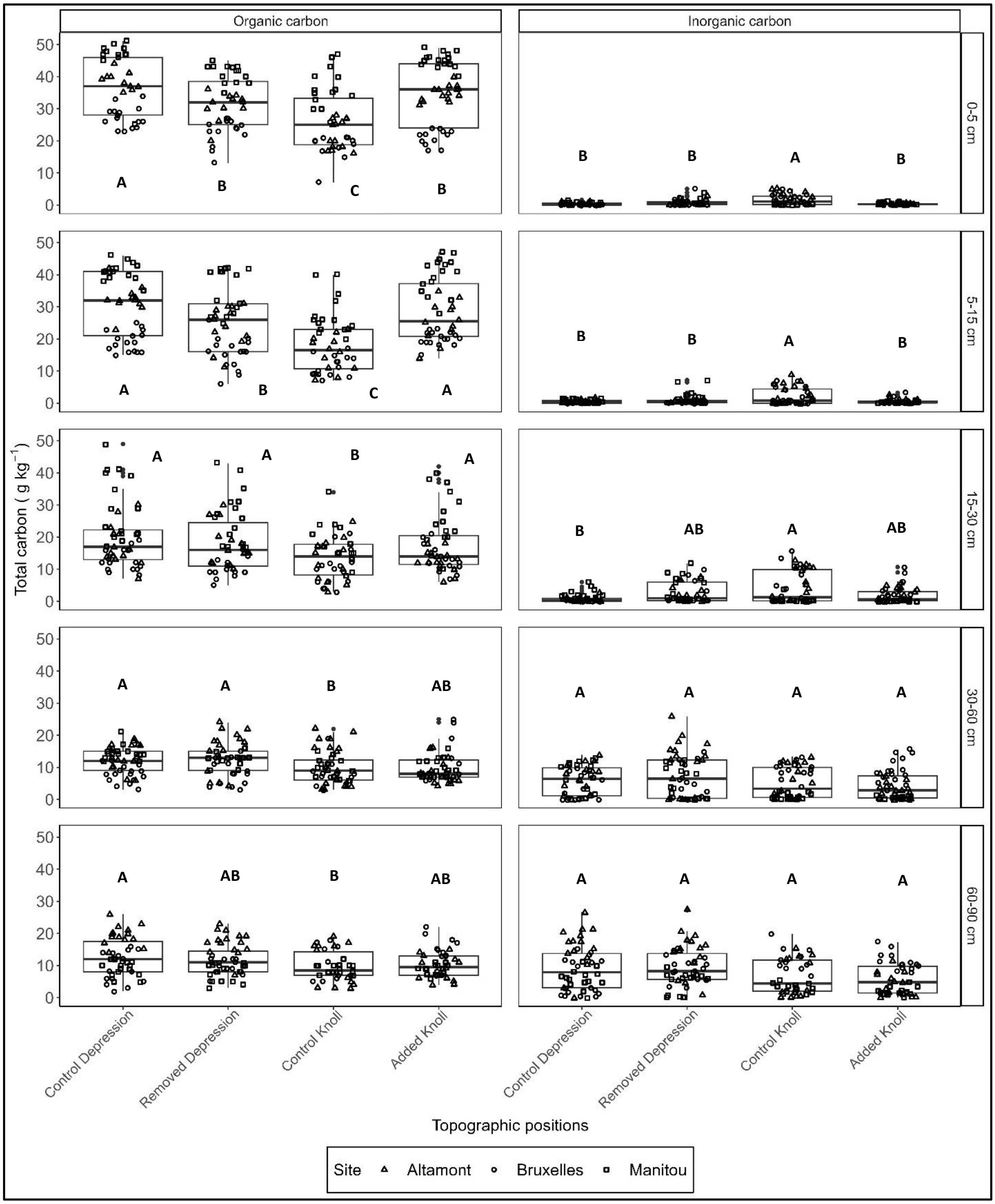

Figure 2. 10. Boxplot distributions of organic and inorganic carbon concentrations (g kg^{-1}) of fall soil samples from years 2021-2023, by depth, treatment and site. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05. Organic and inorganic carbon concentrations statistically analyzed separately.

concentration compared to the control depression plots, while adding topsoil to the knoll significantly increased organic carbon when compared to the control knoll at the 0-5 cm depth ($P < 0.0001$). Soil organic carbon concentrations were not significantly different between the removed depression and added knoll treatments at this depth.

In general, soil organic carbon concentrations dissipated with increasing depth for all treatments. Organic carbon concentrations between the control depression and added knoll were not significantly different throughout the lower depths of the soil profile (i.e., the 5-15 cm depth and below). The control treatments ("control depression" and "control knoll") were statistically different from each other at all depths, highlighting the inherent variability of SOC by landscape position. By contrast, the soil landscape restoration treatments ("removed depression" and "added knoll") were only statistically different from each other at the 5-15 cm depth; at all other depths SOC concentrations were not statistically different from each other, indicating a reduction in variability of SOC by landscape position post-restoration.

Five of the six soil series (excluding Fifere, the soil series at the Manitou knoll) were classified as moderately to strongly calcareous, but this was exhibited only at depths greater than 15 cm by elevated levels of inorganic carbon (Figure 2.10). By contrast, inorganic carbon concentrations from 0-30 cm depths were a relatively small proportion of the total carbon concentration, even in the control knoll treatment, which had the highest inorganic carbon concentration of all the treatments at these depths. Elevated inorganic carbon levels in the control knoll treatment were expected due to the removal of topsoil high in organic carbon by erosion, leaving subsoil with lower organic carbon exposed. Beyond 30 cm, inorganic carbon concentrations were not significantly different among treatments and were similar to organic carbon concentrations at those depths.

All three sites had little to no carbonates at or near the soil surface, but in the knoll positions at Altamont and Bruxelles, moderate levels of calcium carbonates once found in the subsoil have been exposed by erosion over time. The negative effects of inorganic carbon on productivity at these sites were less severe than in other soils with higher levels of inorganic carbon (Scheider et al., 2023). Addition of topsoil on knolls increased SOC and did not increase inorganic carbon. Smith (2008) and Papiernik et al. (2007) saw benefits of organic carbon diluting inorganic carbon levels at the surface, but none of the sites in this study had levels greater than 50 g kg^{-1} of near-surface inorganic carbon prior to the addition of topsoil. Therefore, all sites in their current condition would be re-classified as having a "weakly calcareous" calcium carbonate equivalent, according to the criteria used in Langman (1986). Sites with lower concentrations of inorganic carbon may have resulted in less negative effects from the removal of organic carbon as compared with more calcareous sites with higher inorganic carbon in the soil profile.

Significant site differences in all depths for SOC concentrations were evident, with SOC values at Manitou greater than those at Altamont, and SOC values at Altamont greater than those at Bruxelles ($P < 0.0001$). P values for treatment effects were $P < 0.0001$ for 0-5, 5-15 and 15-30 cm; $P = 0.0047$ for 30-60 cm depth and $P = 0.0422$ for 60-90 cm depth. Site × treatment interactions at 0-5 cm ($P = 0.0069$), 5-15 cm ($P = 0.0062$), 15-30 cm ($P = 0.3210$), 30-60 cm ($P = 0.0050$) and 60-90 cm ($P < 0.0001$). Through the addition of topsoil, SOC concentrations on the knolls for the two combined surface depths (0-15 cm) increased from approximately 19 to 29 g kg^{-1}, a 1.5× increase, using data averaged among all sites. Even greater increases in SOC concentrations from added topsoil were observed in Minnesota by Papiernik et al. (2009), where SOC increased from approximately 12 to 35 g kg^{-1} (a 2.8× increase) in areas of soil addition in the 0-15 cm depths. In another study near Treherne, Manitoba, where topsoil was added, Smith (2008) measured a 2.1× increase in SOC in the 0-15 cm depth, from 13 to 27 g kg^{-1}. These greater increases in SOC may be the result of starting with even more severely eroded sites with lower SOC concentrations on the knolls, higher SOC in the depressions, or both. Another possible explanation is that two of the three sites used in this research were already managed under no-till conditions, unlike the sites in Minnesota and Treherne, which could be responsible for an increase in SOC on the knolls.

In other studies, Larney et al. (2000a) found that cattle feedlot manure applied to artificially-eroded soils at 75 Mg ha^{-1} (wet weight) increased SOC concentrations under dryland conditions from 10.7 to 11.9 g kg^{-1} (at the 0-7.5 cm depth). This was not significantly different from adding 5 cm of replacement topsoil. Under more moist (i.e., irrigated) conditions, there was no significant increase in SOC from any added amendment. When the long-term legacy effects of manure were measured, Larney and Olson (2018) reported increases in SOC from consecutive manure applications, ranging from 11 to 29% over the checks 14-31 years after application. One specific change was an increase in SOC concentration from 14.7 to 17.5 g kg^{-1} (a 19% increase), significantly longer and greater than effects observed from adding 5 cm of topsoil.

Similar, but not identical, trends exist for SOC stocks (Figure 2.11) as compared to ^{137}Cs inventories. There was a significant treatment effect ($P < 0.0001$), site effect ($P = 0.0370$) and site × treatment interaction ($P < 0.0001$). Over all sites, adding topsoil to knolls significantly increased SOC stocks over the control knoll, from 11.0 $\pm$ 0.78 to 15.0 $\pm$ 0.79 kg m^{-2}, a significant, 36% increase of approximately 40 Mg C ha^{-1}, but still significantly less than SOC stocks in the depressions. Removal of topsoil from depressions caused SOC stocks to decrease from 19.6 $\pm$ 1.06 to 17.1 $\pm$ 0.74 kg m^{-2}, a 13% decrease but not statistically significant from each other, presumably because of higher organic carbon concentrations present at greater depth in the depressions. When sites were individually analyzed, adding topsoil to knolls caused no significant increase in SOC stocks over the control knoll at Altamont or Manitou, though there was a significant landscape effect between knolls and depressions at Altamont. Only at Bruxelles did the added knoll have a significant increase in SOC stocks over the control knoll and was similar to SOC stocks in the control depression. Given the depth of topsoil re-distributed in these field studies (i.e., 15 – 20 cm), there were no significant reductions in SOC stocks from removing topsoil from the depressions and no significant increases in adding topsoil to the knolls at two of three sites. This may lead to speculation of whether a greater depth of topsoil should have been re-distributed at these sites.

Other practices may increase SOC stocks as much or more than soil landscape restoration, but they require multiple years to achieve these gains in SOC concentrations and stocks in what soil landscape restoration achieves in the time it takes to move topsoil upslope. The values from above convert to a 40 Mg C ha^{-1} increase when topsoil is moved upslope. By comparison, Schoenau and Hangs (2020) found that after 21 years of no-till practices, there was an approximate 25% increase in SOC content, at a sequestration rate of 220-454 kg C ha^{-1} yr^{-1}, with the most SOC accumulation

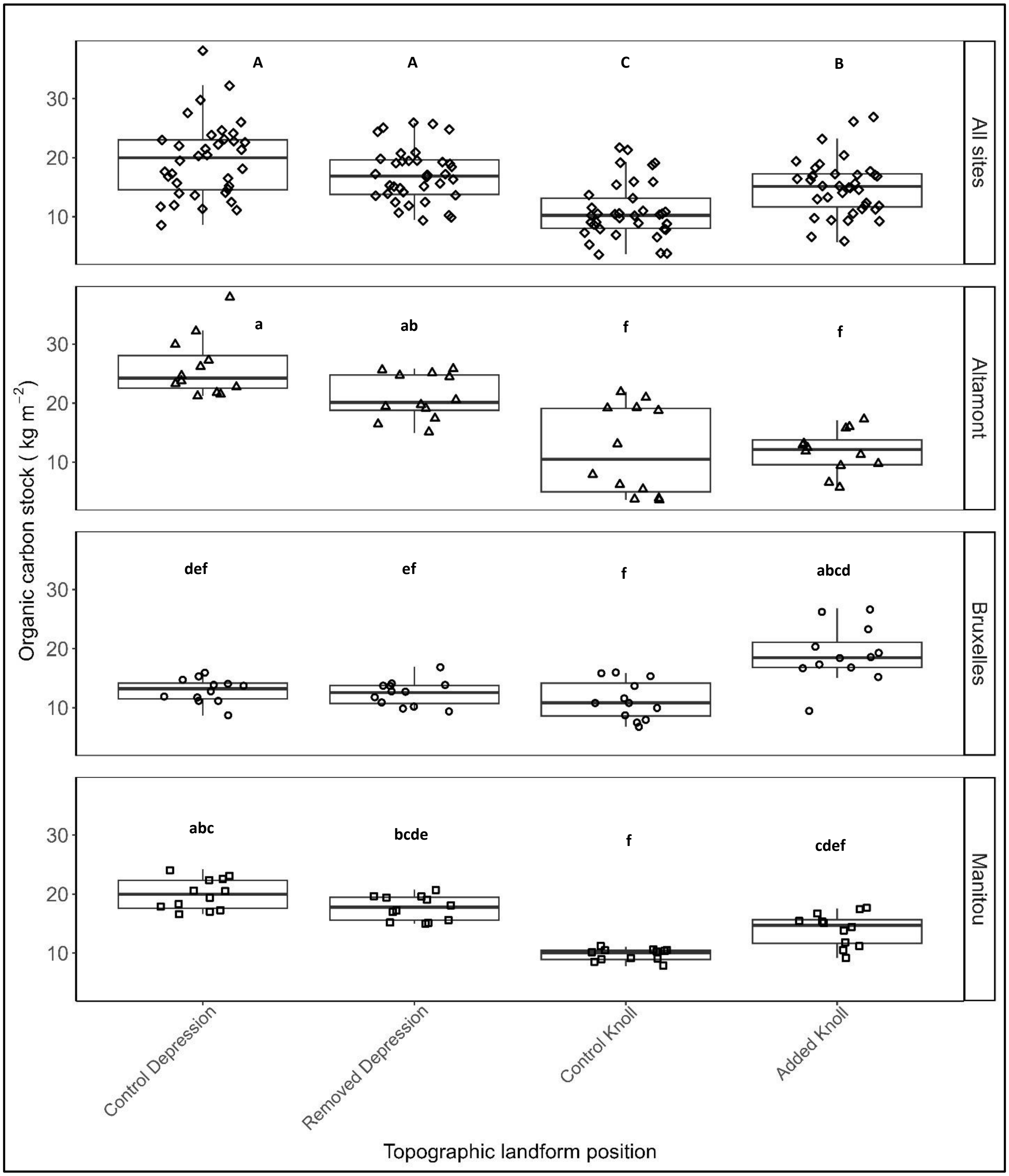

Figure 2. 11. Boxplot distribution of organic carbon stocks (kg m^{-2}) by topographic landscape position and treatment: i) All sites; ii) Altamont; iii) Bruxelles; and iv) Manitou. (Years 2021-2023 only; no 2020 data due to several examples exhausted by ^{137}Cs analyses). Significant treatment effect ($P < 0.0001$), site effect ($P = 0.0370$) and site × treatment interaction ($P < 0.0001$). Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at $\alpha = 0.05$

occurring in soils with the lowest initial SOC levels. Similarly, Nelson et al. (2008) observed soils from upper slope positions have a greater C sequestration potential than other soils within a given catena, with a sequestration rate of 1.4-2.9 Mg C ha^{-1} yr^{-1} from over 8 years in a permanent grass cover. As a reference point, the greatest SOC stocks measured by Schoenau and Hangs (2020) were from soils under 40 yr of no-till management and native prairie soils ranged from 41-48 Mg C ha^{-1}. Peng et al. (2023) found, on average, cover cropping for at least 5 years throughout North America sequestered 3.55 Mg C ha^{-1} (0–15 cm depth) with a sequestration rate of 240 kg C ha^{-1} yr^{-1}, increasing SOC from control treatments by 8% as concentrations and 7% as stocks.

Pooled site data (Figure 2.11) indicates a significant increase in SOC stocks through the addition of topsoil, similar to the increase observed with ^{137}Cs (Figure 2.9). While ^{137}Cs concentrations tend to become non-detectable beyond the 15-30 cm depth, organic carbon concentrations approximating 10 g kg^{-1} were commonly observed throughout soil profiles to the 60-90 cm depth. With only the surface 15-20 cm of the soil profile being manipulated by soil landscape restoration, a greater proportion of the ^{137}Cs was redistributed than SOC, which is found deeper in the soil profile than ^{137}Cs. This would explain why the addition of topsoil to eroded knolls increased ^{137}Cs inventories to those found in the depressions (not significantly different) but increased SOC stocks were still significantly lower than in the depressions.

When SOC concentrations were converted to SOC stocks, the depression at Altamont was observed to have the highest SOC stocks; Manitou SOC concentrations were highest across all treatments at depths 0-5, 5-15 and 15-30 cm; at lower depths, SOC concentrations were highest at the Altamont site. SOC stocks are significantly different by site, by treatment and by site × treatment interaction. This is best explained in that the Manitou site has the highest overall SOC concentrations at the 0-5 cm and 5-15 cm depths; however, the Altamont and, to a lesser degree, the Bruxelles sites have greater SOC concentrations at lower depths. When converted to SOC stocks, the Altamont and Manitou depressions are significantly higher than the Bruxelles depression. When sites were considered individually, results vary in the degree to which SOC stocks are increased, as indicated by a significant site by treatment interaction. At Altamont, adding topsoil to the knoll did not increase SOC stocks significantly from the control knoll; at Manitou, adding topsoil did not significantly increase SOC stocks above the control knoll or the depression treatments. Only at Bruxelles did adding topsoil significantly increase SOC stocks over the control knoll and levels similar to the control depression. This will be important in the next chapter when available water holding capacity (AWHC) is measured and assessed for its effect on crop responses.

It is possible that adding more than 15-20 cm of topsoil could provide a greater benefit on the knolls, as long as topsoil removals from depressions were conducted over wider areas instead of deeper into the soil profile (i.e., no more than 15 cm of topsoil). However, for the three sites examined together in this study, neither the ^{137}Cs inventory data nor SOC stocks data where topsoil was removed from the depression was significantly lower when compared to the corresponding control depressions where no topsoil was removed. Given the more dynamic nature (i.e., the high spatial and temporal variability) of carbon throughout the solum and the landscape than the conservative tracer ^{137}Cs, SOC stocks serve as a supporting indicator, though not necessarily a sole indicator, of soil erosion and potential productivity status.

2.4.4. Soil physical properties

2.4.4.1. Bulk density

Bulk densities at the surface depth (0-5 cm) were only significantly different between landscape positions (Table 2.5). Altamont and Manitou sites had higher bulk densities on the knolls than in the depressions. The subsequent depth (5-15 cm) had a statistically significant site × treatment interaction in which the bulk densities of the Manitou knolls (control and added) were significantly lower than most of the other sites and treatments. At the maximum depth sampled (60-90 cm), there was only a significant site effect, in which bulk densities at Bruxelles were significantly higher than those at Manitou. This difference reflected the contrasting parent materials found at the three sites, with higher amounts of sand found at Bruxelles and higher clay content at Manitou. At none of the depths was there a significant treatment difference in bulk density between control plots and plots with added or removed topsoil. This indicates that equipment used in the landscape restoration process did not cause significant artificial compaction from the movement of topsoil. Similarly, Smith (2008) found no significant difference in bulk density between addition and control plots.

Table 2. 6. ANOVA for bulk density (g cm^{-3}) by depth, 2023.

Site	Position	Treatment	0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm
Altamont	Knoll	Control	1.30 a	1.38 a	1.42 bc	1.50 ab	1.51 ab
		Added	1.27 a	1.40 a	1.43 bc	1.27 ab	1.41 ab
	Depression	Control	0.80 b	1.37 a	1.52 ab	1.65 a	1.72 ab
		Removed	0.83 b	1.39 a	1.43 bc	1.42 ab	1.65 ab
Bruxelles	Knoll	Control	1.12 a	1.45 a	1.86 a	1.76 a	1.59 a
		Added	1.12 a	1.35 a	1.46 ab	1.53 a	1.89 a
	Depression	Control	1.12 a	1.35 a	1.32 bcd	1.29 ab	1.38 a
		Removed	1.02 a	1.18 ab	1.33 bcd	1.34 ab	1.56 a
Manitou	Knoll	Control	1.05 a	0.97 b	1.08 d	1.04 b	1.20 b
		Added	1.00 a	0.95 b	1.19 cd	0.96 b	1.48 b
	Depression	Control	0.83 b	1.13 ab	1.27 bcd	1.16 ab	1.29 b
		Removed	0.94 b	1.23 ab	1.16 cd	1.21 ab	1.36 b
		n	46	48	48	47	47
P value (α =0.05)	Site		0.0690	<0.0001	<0.0001	<0.0001	0.0231
	Treatment		0.0012	0.8100	0.3425	0.4723	0.1477
	Site × Treatment		0.0423	0.0240	0.0002	0.0471	0.1353

2.4.4.2. Aggregate stability

Analysis of variance of the fraction of weighted water-stable aggregates produced a significant site effect (P = 0.0003), in which the Altamont site had significantly higher water-stable aggregates than the other two sites, which was unexpected given the degree of erosion measured at this site (Table 2.6). It appears that the type of parent material and soil texture may have a greater influence on aggregate stability than management practices such as tillage system.

Table 2. 7. Descriptive statistics and ANOVA for weighted fraction of water-stable aggregates (0-15 cm), sampled summer, 2021.

Site	Landscape Position	Treatment	Number of samples	Mean	Std Error of the Mean	CV	Min	Max
Altamont	Knoll	Control	4	0.74	0.04	10	0.64	0.80
		Topsoil Added	4	0.82	0.05	11	0.69	0.89
	Depression	Control	4	0.84	0.02	4	0.80	0.87
		Topsoil Removed	4	0.69	0.06	18	0.53	0.82
Bruxelles	Knoll	Control	4	0.74	0.05	13	0.61	0.82
		Topsoil Added	4	0.69	0.02	6	0.64	0.74
	Depression	Control	4	0.60	0.05	17	0.52	0.74
		Topsoil Removed	4	0.49	0.07	30	0.30	0.66
Manitou	Knoll	Control	4	0.75	0.00	1	0.74	0.76
		Topsoil Added	4	0.73	0.02	4	0.69	0.77
	Depression	Control	4	0.69	0.05	12	0.63	0.78
		Topsoil Removed	4	0.44	0.05	24	0.34	0.57
All Sites	Knoll	Control	12	0.74 a	0.02	9	0.61	0.82
		Topsoil Added	12	0.75 a	0.02	11	0.64	0.89
	Depression	Control	12	0.71 a	0.04	18	0.52	0.87
		Topsoil Removed	12	0.54 b	0.05	30	0.30	0.82
		n	48					
P value			Treatment	$P < 0.0001$				
(α =0.05)			Site	$P = 0.0003$ (Altamont > Bruxelles = Manitou)				
			Site × Trt	$P = 0.3486$				

There was also a significant treatment effect ($P < 0.0001$), in which significantly less water-stable aggregates were observed in the removed depression treatment. While it is expected to see reductions in weighted stable aggregates where topsoil has recently been removed (these sites were sampled once in the growing season following soil landscape restoration), it was unexpected to observe similar values of stable aggregates on the control knoll to that of the added knoll and control depression treatments. Schneider et al. (2023) and Schumacher et al. (2014) observed wet aggregate stability improvements with topsoil replacement. Additional sampling beyond the year after restoration may reveal further changes in aggregate stability as new crops are established in the areas of topsoil removals and contribute to above- and below-ground biomass additions. In another study, short-term increases in aggregate stability of 16% and 58% were observed due to no-till, but in only two of six site-years (Patton et al., 2024). Zhao et al (2023) observed substantial increases in soil organic carbon and macro-aggregates using organic manure after nine years.

2.4.4.3. Hydraulic conductivity

As a measure of water movement into the soil profile, smaller (slower) values, due to restrictive layers or topographic features (Lindstrom et al., 1998), have implications for increased runoff, and the presence of soil compaction; higher values have implications for lack of water holding capacity and elevated risk of leaching of nutrients. Spatial and temporal variability necessitates multiple measurements which can be time consuming and of limited utility, as attested by Larney and Angers (2012).

In this study, hydraulic conductivity rates, given the limited number of measurements taken, were highly variable, as indicated by very high coefficient of variations (CVs) in all cases (Table 2.7). When all sites were considered, hydraulic conductivity rates in the undisturbed, control depressions were numerically higher than all the other treatments and landscape positions. However, none of the treatments or sites were significantly different when an ANOVA was conducted ($P = 0.5433$). Therefore, adding topsoil to eroded knolls did not significantly change hydraulic conductivity rates. Slower hydraulic conductivity rates on knolls than in depressions may reflect a potential increase in water storage capacity, but may also contribute to increased water runoff, which in turn increases the risk of soil erosion by water, and reduce the amount of water stored throughout the soil profile, further reducing crop yield potential.

By contrast, Patton et al. (2024) were able to increase water infiltration by 52 - 64% with cover crops at two of three sites in Arkansas over a two-year study. Schneider et al. (2023) found adding topsoil to upper slopes highly disturbed by tillage increased infiltration rates by 25× from those measured in control plots.

Given the methodology used of determining hydraulic conductivity rates at approximately 30 minutes or when rates stabilized, these values may be over-estimated when compared to measurements taken over a longer timeframe, but this risk would be greater if conducted on heavier-textured soils. Changes in hydraulic conductivity measurements over time would be expected with the development of desirable soil structure once the practice of no-till is implemented on eroded hilltops that have been restored, but it is unclear from this research how much time would be required.

Table 2. 8. Descriptive statistics and ANOVA for hydraulic conductivity (K_{sat}) rates (cm hr^{-1}), 2022-2023.

Site	Landscape Position	Treatment	Number of samples	Mean	Std Error of the Mean	CV	Min	Max
Altamont	Knoll	Control	8	23.2	7.1	86	3.6	66.0
		Topsoil Added	8	24.1	6.7	79	3.6	51.6
	Depression	Control	5	34.6	21.4	139	1.2	115.2
		Topsoil Removed	5	25.1	8.6	77	9.6	49.2
Bruxelles	Knoll	Control	8	11.6	2.5	61	2.4	21.6
		Topsoil Added	8	17.0	7.1	117	3.6	61.2
	Depression	Control	5	24.2	10.0	92	7.2	62.4
		Topsoil Removed	5	13.2	4.0	68	2.4	24.0
Manitou	Knoll	Control	8	19.8	2.9	42	7.2	32.4
		Topsoil Added	8	17.0	7.1	117	3.6	61.2
	Depression	Control	5	45.8	13.0	63	18.0	80.4
		Topsoil Removed	5	8.9	2.8	69	3.6	18.0
All Sites	Knoll	Control	24	18.2 a	2.8	74	2.4	66.0
		Topsoil Added	24	16.3 a	3.5	106	1.2	61.2
	Depression	Control	15	34.9 a	8.6	96	1.2	115.2
		Topsoil Removed	15	15.7 a	3.6	88	2.4	49.2

No significant treatment effect ($P = 0.5433$), site effect ($P = 0.2776$) or treatment × site interaction ($P = 0.2968$).

2.4.4.4. Soil pH

Depending on the depth observed, adding topsoil either did not significantly change soil pH. This was a function of the parent material present at each site (Figure 2.12), with significant site differences and site × treatment interactions present at all depths. The Manitou site consistently has significant lower pH than the other two sites at all depths. P values for site effects by depth were $P = 0.0003$ (0-5 cm), $P < 0.0001$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P < 0.0001$ (30-60 cm) and $P = 0.0035$ (60-90 cm). P values for treatment effects by depth were $P = 0.2341$ (0-5 cm), $P = 0.0008$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P = 0.3351$ (30-60 cm) and $P = 0.0250$ (60-90 cm). P values for site × treatment interactions by depth were $P < 0.0001$ (0-5 cm), $P < 0.0001$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P = 0.0009$ (30-60 cm) and $P < 0.0001$ (60-90 cm).

2.4.4.5 Soil electrical conductivity

Soil electrical conductivity (EC) did not significantly increase through the movement of topsoil from depression to knoll, other than at the Manitou site where salt levels were only slightly elevated near or just above threshold values; as a result, the risk of moving salt-affected topsoil to the knolls was low. (Figure 2.13).

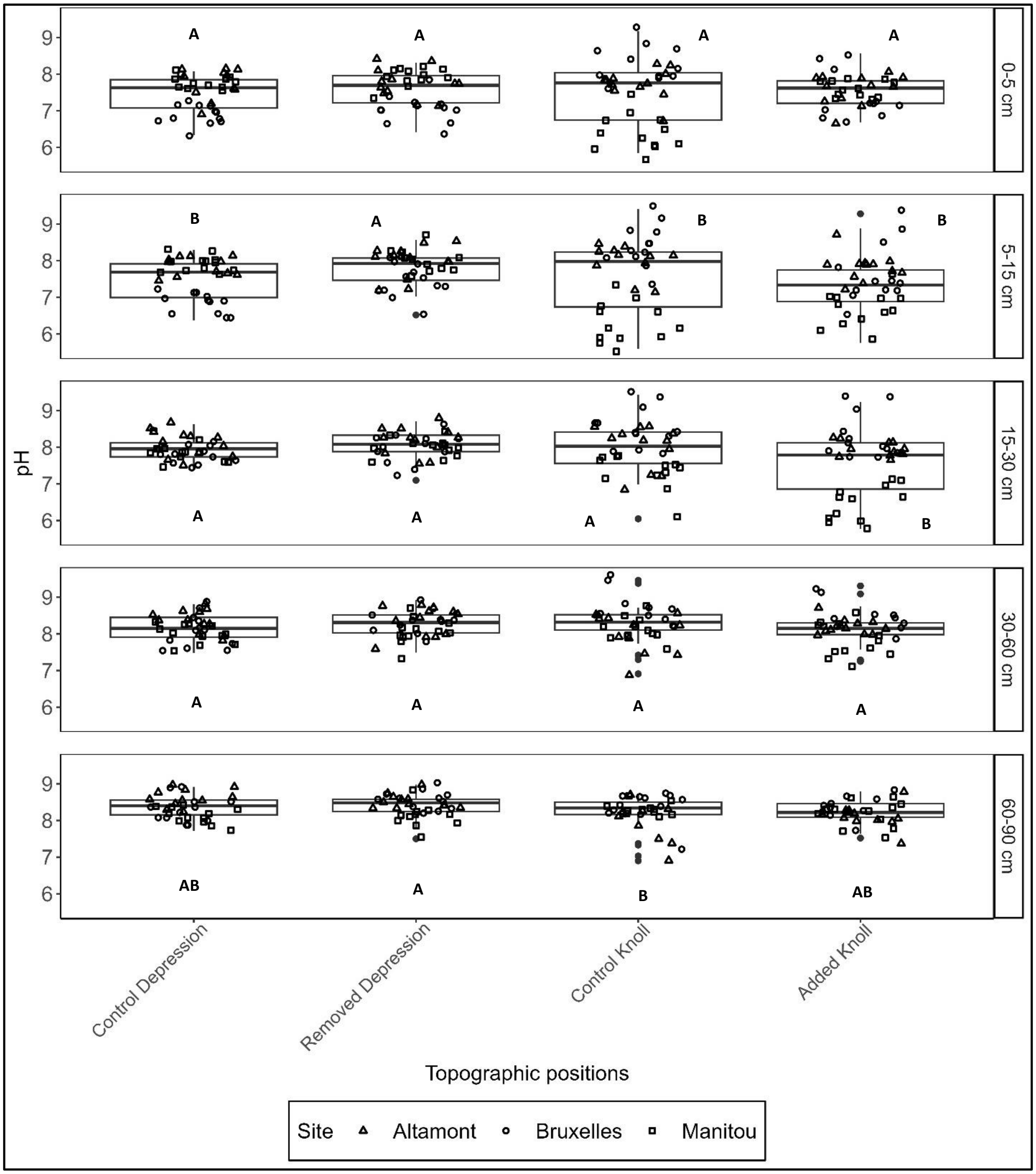

Figure 2. 12. Soil pH values from fall soil sampling (2020-2023), all sites, by depth, landscape position and treatment. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05

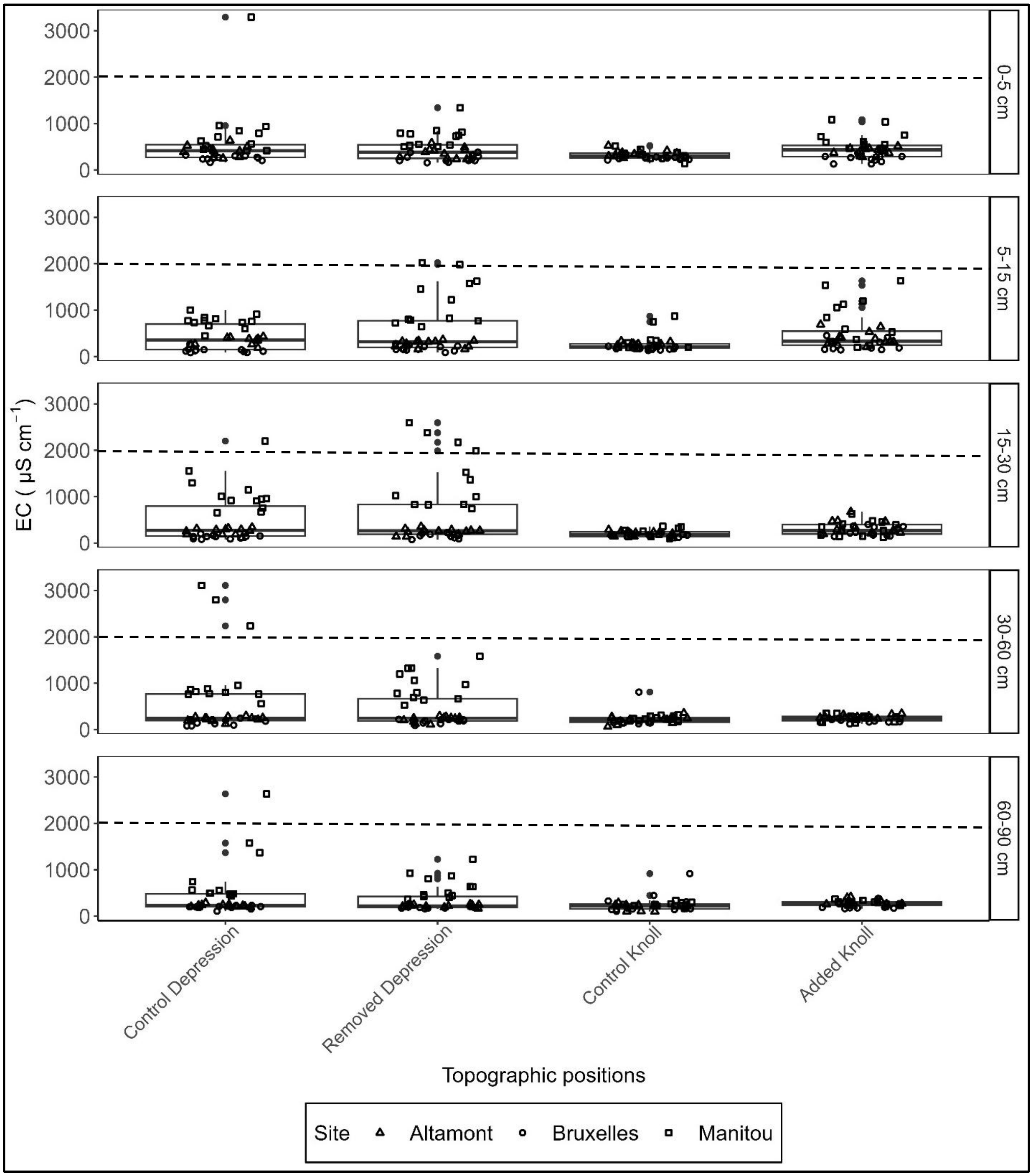

Figure 2. 13. Soil electrical conductivity (EC) values (µS cm^{-1}) from fall soil sampling (2020-2023), all sites, by depth, landscape position and treatment (values less than 2000 µS cm^{-1} are considered non-saline).

2.5. Conclusions

^{137}Cs analyses and subsequent modeling confirmed significant, long-term, unsustainable soil erosion losses on knolls at all three sites. Using ^{137}Cs as a tracer of soil movement suggests the majority of the topsoil removed from the knolls had been redistributed within the rest of the in-field landscape and remained in the field because the major agent of soil movement has been tillage erosion. Soil landscape restoration increased ^{137}Cs inventories on eroded knolls to levels similar to those in depressions. Removing 15-20 cm of topsoil from the depressions in these three sites did not significantly decrease the overall ^{137}Cs inventories from the control depressions.

Soil organic carbon concentrations were not statistically different between added knoll and control depression treatments at all depths. SOC stocks (inventories) at Bruxelles exhibited a similar trend as for ^{137}Cs inventories, which were increased significantly on knolls with added topsoil when compared to control knolls. However, unlike ^{137}Cs inventories, SOC stocks were significantly lower on the added knoll than in the corresponding depressions at Altamont and not significantly different than the other treatments and landscape positions at Manitou. Whether sufficient amounts of SOC were transferred to eroded knolls to sufficiently increase crop productivity (biomass and yield) at all sites will be assessed in the subsequent chapter. Other strategies may need to be examined if it is determined that SOC stocks should be increased to levels similar to those found in the corresponding depressions.

Soil landscape restoration practices did not affect soil bulk density values or hydraulic conductivity rates significantly, but decreased the proportion of water-stable aggregates where topsoil was removed from depressions. Soil pH and EC were not dramatically affected by landscape restoration practices at these sites, but it would be recommended to check these properties prior to conducting landscape restoration practices at other sites.

In terms of quantifying the existence or severity of erosion, these properties, along with SOC and soil survey/landform information, may be insufficient on their own. However, when combined with ^{137}Cs radionuclide conservative tracer inventories and modeling of soil movement and re-distribution, soil loss and deposition rates within a landscape can be quantified and subsequent landscape restoration practices evaluated. Soil landscape restoration should improve soil health indicators under most scenarios; whether this translates into increased crop productivity will be investigated in a subsequent chapter (Chapter 3).

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Chapter 3

Crop response to added and removed topsoil in eroded landscapes

3.1. Abstract

The negative effects of soil erosion on crop productivity as a global issue are often difficult to quantify, predict and overcome. Wind and water erosion can have dramatic effects over numerous, intermittent events, but the largely-unrecognized effects of tillage erosion, which can occur multiple times during a growing season with every pass of a tillage implement, is slowly being realized for its reductions in crop productivity and the associated costs for allowing this phenomenon to continue.

A study was conducted over twelve site-years in south-central Manitoba to determine the effects of soil landscape restoration, where topsoil was removed from lower-lying areas of the landscape and returned to eroded hilltops impacted by tillage erosion. A number of agronomic measurements were conducted over the four years on predominantly wheat and canola crops. Significant, positive biomass responses were observed in two site-years, with significant positive yield responses in four of the twelve site-years. Yield increases from added topsoil were 21 – 58%, with relative hilltop yields as a percentage of depression yields increasing from approximately 50% to 80% or higher. Crop response was influenced by several factors, such as established plant population, crop nutrient (N and P) status, annual effects of weather (growing degree days and precipitation) and available water holding capacity (AWHC) of the soil.

Positive crop response was correlated with several factors, including site (Bruxelles), as well as management factors such as long-term no-till, meeting target plant populations and macronutrient (N and P) requirements, adequate (timely) precipitation events throughout the growing season, and increases in AWHC from the addition of topsoil from depression areas to the eroded hilltops (soil landscape restoration). Future research may require more frequent soil moisture monitoring and other strategies to affirm improved near-surface soil moisture for crop establishment and growth.

3.2. Introduction

3.2.1. Effects of soil erosion

The global effects of soil erosion are well documented (Montanarella et al., 2015) with an average global rate of crop productivity loss at 0.3% per year (den Biggelaar et al., 2004). Yet the relationship between soil erosion and crop productivity is difficult to measure, due primarily to spatial variability, masking of erosion effects by agronomic advances (such as developing higher-yielding plant cultivars), implications of weather and the cumulative effects of successive erosion events (den Biggelaar et al., 2001; Bakker et al., 2004; Bakker et al., 2007). Lobb and Li (2024), in their review of soil erosion assessments in Canada over the past 50 years, found reductions in soil erosion risk were greater in western Canada than in eastern Canada. This was largely due to the dominantly corn-soybean crop rotations in eastern Canada, which utilizes more tillage and produces less crop residue cover (as a row-crop system) than a solid-seeded wheat-canola system that dominates the Prairies in western Canada. Despite these improvements, economic assessments of crop production losses due to soil erosion are approximately $3 billion per year, with cumulative losses since the 1960's estimated at $60 billion (Lobb and Li, 2024).

Part of the challenge is identifying the degree and extent of erosion at which crop yield losses become noticeable to the producer, but well before erosion effects are so severe that rehabilitation efforts and the economic losses are too great to warrant intervention. Determining depth of lost topsoil can be difficult, having to rely on either historical soil survey records or use of radionuclide tracers such as ^{137}Cs to determine erosion rates (Lobb et al., 1995). In southwest China, Duan et al. (2016), using degree of erosion classes (none, slight, moderate and severe), reported an average soil erosion rate of 0.77 mm year^{-1}, mean absolute corn yield loss of 0.01 Mg ha^{-1} year^{-1} and relative yield loss of 0.10% year^{-1}. These authors recommended soil erosion should be controlled once the "moderate" level is reached; yet, on moderately eroded sites, rehabilitation measures often produce no crop productivity responses (Schneider et al., 2021).

On severely eroded sites in southern Ontario, Battiston et al. (1985) observed drought stress caused by soil erosion reduced crop yields by 32 – 43%. Similarly, in Alberta, Larney et al. (1995) found yields were reduced by 50% by removing 7-17 cm of topsoil, depending on the original thickness of the A horizon prior to topsoil removal. Weesies et al. (1994), after 10 years of erosion studies on three Indiana soils, found corn *(Zea mays,* L.*)* yields on severely-eroded soils decreased 9-18% and soybean *(Glycine max,* L.*)* yields decreased 17-24%, compared to slightly-eroded soils. The "tipping point" of the long-term effects of tillage erosion result in the continued downslope movement of subsoil from the knolls onto the mid-slopes and eventually the depressions, burying the topsoil and reducing yield productivity in the downslope positions as well as the knolls (Lobb, 2011).

The largest impact of soil erosion causing reductions in crop productivity is the decreased water holding capacity of the soil (Larsen et al., 1983; Lal and Moldenhauer, 1987; Duan et al., 2016; Lin et al., 2019), coupled with increased variability of soil properties within and between fields. Duan et al. (2011) observed 21 black soil profiles in China and found organic matter content and available water holding capacity decreased consistently as the amount of topsoil lost to erosion increased, representing a 9.6% productivity reduction over 100 years (or a 1% productivity reduction for each 1 cm of topsoil that erodes). Secondary effects of soil erosion include the loss of fertility, such as total nitrogen, total phosphorus and soil organic matter (Zhang et al., 2021), as well as the degradation of parameters for a suitable seedbed for crop establishment, such as aggregate stability (Allen et al., 2011).

3.2.2. Crop effects from soil erosion

Estimates of crop yield losses due to soil erosion for corn, soybeans, wheat *(Triticum aestivum, L.)* and cotton *(Gossypium,* L.*)* in North America were calculated by den Biggelaar et al. (2001) and den Biggelaar et al. (2004) at an average rate of 0.3% year^{-1}. These yield losses appear relatively small on a global scale, but with wide variations between crops, soil orders and geographic regions when considered on a regional or local level. Zhang et al. (2021) observed decreasing crop yield sensitivity to erosion from soybean to corn to wheat, which is directly related to the decreasing rooting depths of these crops (soybean > corn > wheat) and inversely related to the water use efficiency of these crops (wheat > corn > soybean). In Alberta, Izaurralde et al. (1998) showed spring wheat yields on two soil types decreased by more than 50% of yields from non-eroded topsoil, with 20 cm of topsoil removed from a forest soil (Typic Cryoboralf) more severely affected than 20 cm of topsoil removed from a grassland soil (Typic Cryoboroll). By contrast, there are some soils that will be more resistant to soil erosion than others; in Montana, for example, different depths of artificial removal of topsoil (0, 6, 12, 18 cm) produced no differences in soil organic matter (SOM) content, particulate organic matter (POM) content, mineralizable nitrogen and water stable aggregates (WSA) in the surface 15 cm, as well as no effect on soil water at planting nor wheat yields from 1998-2001 (Allen et al., 2011). Reductions in crop yields tend to be more sensitive to erosion effects than crop biomass (Gao et al., 2015; Larney et al., 2003). Furthermore, the cumulative effects of soil erosion may cause greater losses if not addressed in a timely fashion (den Biggelaar et al., 2001; Lal, 1998).

3.2.3. Simulated erosion (desurfacing) studies

The inconsistent relationship between soil erosion and crop response is partially due to the type of methodology used in various erosions studies (Bakker et al., 2004). For every 10 cm depth of soil loss, an average reduction in crop productivity of 4.3% using comparative-plot methods, a 10.9%

reduction for transect methods; and a 26.6% reduction was observed for desurfacing experiments. The latter two methods tend to over-estimate the effect of soil erosion, as artificially-induced erosion is a one-time event that would otherwise be catastrophic in nature from the complete removal of a specific depth of topsoil across the study area. Several of the experiments conducted are desurfacing experiments and are summarized below, highlighting the wide range of crop responses to artificial soil erosion.

In Iran, Gorji et al. (2008) found artificial soil erosion to 20 cm depth had a significant impact on dry matter and straw yields in wheat, but not on grain yield. Each centimeter of topsoil removed resulted in a reduction of 0.8% in dry matter. In Nigeria, removal of 5 cm of topsoil reduced corn yield by 55% (Oyedele and Aina, 2006). Larney et al. (1995) conducted simulated erosion depths of 0, 5, 10, 15 and 20 cm, with reduced spring wheat yields ranging from 48 kg ha^{-1} (a 1.8% reduction) to 213 kg ha^{-1} (an 8.5% reduction). A Manitoba study (Ives and Shaykewich ,1987) in which topsoil desurfacing of 0, 5, 10 and 20 cm of Ah horizon from Black Chernozems and Dark Gray Luvisols decreased wheat yields with increasing amounts of removed topsoil, highlighted the important role of SOM in crop productivity. Like other studies, high rates of fertilizer did not restore yields to those of the uneroded soil without fertilizer, especially in lighter-textured soils, suggesting other factors (such as water-holding capacity) were negatively affected by soil erosion.

3.2.4. Potential solutions for restoring productivity to eroded soils

Larson et al. (1983) recommended the application of numerous inputs required for productivity restoration, which included macronutrients (N, P and K), organic amendments (manure, organic wastes, etc.), cover crops, micronutrients (Zn), lime, and irrigation and drainage. No-till should be the preferred method of planting crops under eroded conditions. McGuire (2024) advised to use soil-building practices that maximize photosynthesis and minimize tillage rather than to rely on products such as inoculants, bio-fertilizers, bio-stimulants and bio-chemicals, to improve the health of soils.

3.2.4.1. Increasing inputs (seed and fertilizer)

While there are researchers that generally recommend additional inputs were sufficient to restore production to levels of non-eroded soils (Pierce and Lal, 2017), many other researchers, from multiple locations, found that additional fertilizers could only partially restore the negative effects of soil erosion (Gorji et al., 2008 (Iran); Larney et al., 2011 (Alberta); Izaurralde et al., 1998 (Alberta); Ives and Shaykewich, 1987 (Manitoba); Eck, 1987 (Texas)). In Montana, Allen et al. (2011) found commercial fertilizer would maintain crop yields on soils more resistant to the effects of soil erosion.

In terms of what type of fertilizer to add, Izaurralde et al. (1998) and Eck (1987) recommended both N and P as the two main macronutrients. Others (Gorji et al., 2008) saw only phosphorus had a significant effect on wheat yields, partially compensating for the negative erosion effects. Though less important, potassium (K) fertilizer may induce a crop response on sandy-textured soils where K tends to be limiting (Manitoba Agriculture, Soil Fertility Guide).

3.2.4.2. Irrigation

The artificial addition of water to agricultural soils to assist in crop growth can overcome productivity limitations due to limited natural precipitation and soils with low water holding capacity. Increasing the ability of soil to hold more water, regardless of its source, is a more long-term and cost-effective solution. McGuire (2025; 2014) argued that soils with low SOM can be highly productive because many of the soil properties which would suggest low soil health can be overcome with a reliable, regular supply of water through irrigation. Furthermore, irrigation can increase biomass productivity in otherwise droughty conditions, which may increase SOM over time. However, under eroded soils, Zhang et al. (2021) found irrigation, like additional fertilizer, can increase crop yields but cannot restore yields to pre-erosion levels once the erosion depth is greater than 20 cm. In irrigated studies in Alberta, neither fertilizer nor irrigation were sufficient practices for replacing topsoil in terms of crop yield productivity (Larney et al., 2011; Larney et al., 1995).

3.2.4.3. Increasing available water holding capacity (AWHC)

Hudson (1994) reported that increasing SOM increased AWHC by increasing field capacity to a greater extent than increasing wilting point. Regardless of soil texture, AWHC more than doubled when SOM increased from 0.5 to 3%. Similarly, Olness and Archer (2005) observed for every 1% increase in soil organic carbon, there was a resulting 2 – 5% increase in AWHC (in soils containing less than 2.5% organic carbon and less than 40% clay). However, the amount of time and organic material required to increase SOM by such amounts at the field scale may be impractical (Magdoff and van Es, 2021). Others have determined that the increase in soil organic carbon has a limited effect on available water holding capacity, whereas a 1% (10 g C kg^{-1} soil) increases AWHC by only 1.16 mm H_2O 100 mm $soil^{-1}$ (Minasny and McBratney, 2017). Generally, AWHC was found to be strongly correlated with clay content, followed by bulk density and organic matter (Bordoloi et al., 2019).

3.2.4.4. Increase crop residues on eroded soils

The remaining practices focus on one of two possible remedies to lost productivity on eroded soils: either improve the soil condition with *in situ* soil and crop management practices, or bring in additional amendments from other parts of the landscape, from within the same land parcel or from another land parcel.

Effects from crop residue studies on soil carbon are mixed: while increasing crop residue production *in situ* (through design and selection of crop rotations) increased soil cover and may have reduced further soil erosion, it was unclear whether changing crop rotation alone was sufficient to increase SOC/SOM levels in soils that resulted in a subsequent increase in productivity. In West Lafayette, IL, after 16 years of crop rotation research, comparing continuous corn, corn-soybean, corn-soybean-wheat and continuous soybean rotations, Hickman (2002) concluded differences in crop residue levels did not make meaningful changes to organic matter levels in a silty clay loam (Typic Haplaquoll). By contrast, Lal et al. (1994) did observe a crop rotation effect in central Ohio on soil organic carbon, with continuous corn having a greater effect than corn-soybean, which was also greater than a corn-oat-meadow rotation. Dick et al. (1991) recommended, "management systems that include rotations with high residue-producing crops and reduced tillage result in greater SOC and N, and may improve soil productivity."

Experimentation in the physical removal and addition of crop residues provided additional understanding of the role of crop residue on soil moisture retention and crop yields. In Nebraska, Van Donk and Klocke (2012) found crop residue was responsible for an additional 76 – 89 mm of soil water and an additional 1067 – 1569 kg ha^{-1} (17 - 25 bu ac^{-1}) of corn. For soybeans, the increase in soil water was 64 – 127 mm and an increase of 538 – 672 kg ha^{-1} (8 -10 bu ac^{-1}). In Alberta, wheat straw applied at 14.6 – 17.0 Mg ha^{-1} dry weight resulted in the lowest yields of all other treatments (Larney et al., 2003), likely as a result of immobilization of nitrogen. In the semiarid region of Canadian prairies (Swift Current, SK), Cutforth and McConkey (1997) found growing season evapotranspiration (ET) was not affected by stubble height. but seeding wheat into tall (>30 cm) stubble increased grain yield and water use efficiency by about 12% over wheat seeded into cultivated stubble, with wheat seeded into short (15 cm) stubble produced intermediate results. Tall stubble also created microclimate effects such as reduced wind speed and soil temperature. Hartman (2008) provided estimates of the quantity and nutrient content of straw and chaff, as well as recommendations on the amounts of crop residues needed to maintain protection of the soil from wind and water erosion, along with the tolerable amount and frequency of straw removal that would still maintain soil organic matter levels. It was recommended not to remove crop residues from drought-prone regions; this could also be interpreted for drought-prone areas of a field (i.e,, eroded hilltops) in a precision agriculture scenario.

In a soybean experiment conducted by Mohr (2019), four sites across Manitoba experienced on average 1-3^{o}C lower soil temperatures at seeding than where wheat straw was removed, but residue management had limited effects on other factors such as plant stand, soybean yield and seed quality. It is possible that increasing crop residues on eroded hilltops may have an increased positive effect on soils where moisture conservation would be beneficial (Baloch et al., 2025).

3.2.4.5. Manures, compost and other organic amendments

Unlike fertilizers, where there is only a partial recovery in the productivity of eroded soils, Larney et al. (2009) demonstrated that the importing and inclusion of amendments such as livestock manure and compost was more effective at restoring crops yield than either additional fertilizer or added topsoil. Prior to this, Larney et al. (2003) showed that the productivity-enhancing effect of manure was strongly dependent on the organic carbon content of the recipient soil, with low-SOC soils showing the largest gains in productivity.

Miller et al. (2019) concluded the legacy effects of manure can significantly affect soil nutrient supply over time but the effect on crop response was variable and site-specific. The drawbacks of using organic amendments is their limited supply and transport costs (McGuire, 2018) and the need to assess the choice of amendment based on the initial soil degradation level, nutrient and carbon content, as well as potential toxins present in the amendment and the desired rate and frequency of application (Larney and Angers, 2012).

3.2.4.6. Cover crops

Peng et al. (2023), summarizing numerous cover studies throughout North America, noted cover crops used for longer than 5 years produced significant *in-situ* increases in the surface 15 cm for SOC, total nitrogen, water-stable aggregates and potential carbon mineralization.

In eroded soils, the primary benefit for utilizing cover crops would be improved soil moisture from increased water infiltration and water holding capacity. However, establishment of cover crops on eroded soils that lack sufficient water holding capacity may be challenging during times of low rainfall and dry soils (Morrison and Lawley, 2021). Rodrigo-Comino et al. (2020) suggested use of common vetch (*Vicia sativa* Roth.) as a cover crop to reduce soil erosion. SARE (2007) recommends fast-establishing grass cover crops (including winter cereals such as fall rye *(Secale cereale, L.)*) on eroded soils, with termination of cover crops at least two to four weeks before planting the cash crop to offset the risks of soil water depletion and other effects of cover crop residues. Of similar importance to the timing of the termination is the critical amount of biomass produced, which may determine when a cover crop should be terminated to avoid yield reductions to the subsequent cash crop. Unfortunately, this value is highly variable and site-specific.

3.2.4.7. Soil landscape restoration (SLR)

Historically, the practice of soil landscape restoration, where topsoil that has been transported downslope primarily via tillage erosion and returned to the eroded hilltops, was documented in France in the 1930's (Dale and Carter, 1955). One of the earliest research activities into adding topsoil to eroded soils in North America was in Nebraska, where corn yields increased 10 – 20% from 10 – 20 cm of added topsoil (Mielke and Schepers, 1986). Larney et al. (2003) found replacing 50% of the topsoil removed (i.e., 4 – 4.5 cm topsoil added) exhibited a positive crop biomass response in six of twelve site-years and positive grain yield responses in only one of ten site-years, with a lower crop yield response than from added manure. Fertilized plots equalized the N-supplying power, often masking the treatment effects. A summary of previous soil landscape restoration trials and crop yield responses is provided in Table 3.1.

Table 3. 1. Summary of crop yield increases from the addition of topsoil in soil landscape restoration.

Research	Year	Site	Topsoil Added (cm)	Years after restoration	Crop	% Yield Increase (actual change in kg ha^{-1})	Relative Weather Cond's
Schneider et al. (2021)	2006-2011	MN	15-20	1 - 6	Corn Soybean	20-49% 12-59%	Dry
Liang et al. (2018)	1997	OH	20	15	Corn	47% From 7450 to 10950	
Smith (2008)	2005	Treherne MB	10	1	Barley	31% From 1810 to 2365	Wet
	2006	Treherne MB	10	2	Pea	64% From 1249 to 2049	Dry
	2005	Brookdale MB	20	2	Oat	10% From 2831 to 3121	Wet
	2006	Brookdale MB	20	3	Flax	40% From 1907 to 2679	Dry
	2006	Bruxelles MB	10	1	Wheat	133% From 796 to 1856	Dry
	2006	Swan Lake MB	10	1	Flax	94% From 404 to 784	Dry
Erb (2005)	2003	Brookdale MB	10	<1	Flax	18% From 1195 to 1407	Dry
					Pea	67% From 1833 to 3061	Dry
Larney et al. (2009)	1990-2006	Lethbridge AB	5	1-16	Wheat (dryland)	20% From 1900 to 2280	31-183% of normal
					Wheat (irrigated)	14% From 2880 to 3280	Dryland + 100 to 200 mm
Verity and Anderson (1990)	1986	SK	5-15	1	Wheat	45-58% From 914 to 1443	Drier
	1987	SK	5-15	2	Wheat	42-88% From 1143 to 2150	Wetter

Experiments conducted by Erb (2005) concluded adding topsoil increased soil nutrients, improved point-in-time soil moisture and temperature conditions, but did not always produce a crop yield response. In Minnesota, long-term studies on soil-landscape rehabilitation (a.k.a. soil landscape restoration) measured significantly increased gravimetric soil water content in the top 20 cm (soil addition layer only) from the control plots in the upper slopes by 0.05 – 0.12 g g^{-1} (5-12%) at fall sampling and by 4-7% at spring sampling (bulk density for these samples 1.30 – 1.40 g cm^{-3}) (Papiernik, Koskinen et al., 2009). Added topsoil increased crop biomass by 12-40% at two sites, but significant yield increases only occurred at a severely eroded site in Minnesota (Schneider et al., 2021). Other concerns addressed from this study included no decrease in productivity from added topsoil over the 2006-2011 sampling period; and no evidence of soil compaction due to restoration activities (Papiernik et al., 2009). By contrast, removed topsoil from the lower landscape positions (Schneider et al., 2021) resulted in 0.8 – 2.5 Mg ha^{-1} lower corn yields and 0.5 – 1.3 Mg ha^{-1} lower soybean yields. Soil removal at both Minnesota and South Dakota sites reduced biomass yields by 5 – 33%, along with significant reductions in Olsen P (0-30 cm); and extractable K (0-15 cm) in some of the lower slope positions (Schneider et al., 2023). Soil addition plots (all upper slope positions) significantly increased plant available N (0-60 cm), Olsen P (0-45 cm) and extractable K (0-30 cm) (Schneider et al., 2023).

Concerns over moving saline topsoil upslope were addressed by Erb (2005), who observed only minor increases in salt concentration (EC) from soil addition that would be insufficient to negatively affect crop growth. Provided topsoil sources were not from areas with near-surface salinity, this should not be a regular concern with this practice, but it would be prudent to soil test prior to topsoil movement.

Concerns over shifting weed communities as a result of topsoil movement were shown to change overall weed populations only in the short term (2 years), through weed seed burial from soil additions and from soil removal. After two years, there was no difference between control plots and soil landscape restoration plots from the same landscape position. (Schneider et al., 2025).

Previous economic analyses (Bosma, 2004; Hacault, 2011) have demonstrated the feasibility of this practice. Although current adoption rates of this practice by Canadian producers are modest (Statistics Canada, 2023), there is huge potential to utilize this practice in such a way that increases crop productivity, reduces the effects of tillage erosion and restores the long-term productivity of the most sensitive areas in the agricultural landscape.

3.2.5. Study objectives

The objectives of this study were: 1) to measure differences in crop productivity between landscape positions and the effects of soil landscape restoration (specifically, topsoil removal from depressions and topsoil additions to eroded hilltops) to assert the benefits of added topsoil surpass the reductions of topsoil removal; and 2) to determine the dominant factors behind any changes in crop productivity from soil landscape restoration practices, including increased available soil moisture, increased nutrient availability, plant counts and any factors that could mask changes in crop productivity (low plant stands, high weed pressure and extremely dry weather conditions).

3.3. Materials and methods

3.3.1. Local weather data for growing season conditions

Weather data was obtained from a variety of weather stations. At the Altamont site, an Environment and Climate Change Canada weather station was used, located at Deerwood, MB, approximately 8.5 km from the Altamont site (station ID 29886; 49.4^{o}N; -98.32^{o}W; 341.4 m elevation). For the Bruxelles site, an Agriculture and Agri-Food Canada in-field weather station was located in the same field, approximately 350 m from the study area, at 49.7316°N, -98.88364°W; and for the Manitou site, a Manitoba Agriculture weather station located at 49.2451°N, -98.5453°W, approximately 6.4 km from the site was used. All weather data was downloaded using the Weathercan package in R (LaZerte et al., 2018).

3.3.2. Spring soil temperature

Soil temperatures at a depth of 5 cm were measured using four probe-type thermometers (Master Chef™ instant-read cooking thermometer), placed diagonally across plant rows with an overall distance of 1 – 2 m between the first and fourth thermometers. Depending on the year, soil temperatures were measured three to six times, from prior to planting to approximately three weeks after plant emergence, in the years 2021 to 2023.

3.3.3. Spring plant counts

Four adjacent rows each one meter long were selected within each plot area. The number of plants per square meter were counted early in the growing season after sufficient time for the crop to fully emerge.

3.3.4. Soil water

Soil samples were collected from each plot, one sampling point per sampling event, over four events per growing season to a depth up to 90 cm using a Dutch auger and sealed plastic containers with twist lids. Sample depths used were 0 – 5 cm; 5 – 15 cm; 15 – 30 cm; 30 – 60 cm and 60 – 90 cm. Bulk density was determined using a metal corer (dimensions 4.8 cm diameter and 5.0 cm height) for nearly all surface depths and occasionally for the deeper depths to get a reasonable approximation of the soil bulk density values by depth for determination of volumetric water content and ultimately total mm of water in the soil profile. Fall, 2023 soil sampling involved the collection of a separate set of soil samples (approximately 240 samples in total) using a coring tube of a known diameter (either 44 mm or 38 mm, depending on the sampling equipment used at each site) and soil sample length according to sampling depths listed above to determine bulk density. Samples were transported back to the laboratory at Agriculture and Agri-Food Canada, Portage la Prairie site and placed in a cooler at 5^{o}C until processed for gravimetric soil moisture determination. Soils were weighed wet, placed into metal containers, dried in soil drying ovens at 105^oC for 24 hours, allowed to cool and were weighed a second time to determine oven-dry weight and calculate gravimetric soil moisture content for each sample. Analysis of soil moisture using AWHC was determined using critical moisture retention parameters, e.g., field capacity (FC) and permanent wilting point (PWP), along with sampling dates and assumed rooting depths at those times:

1. Late May – early June: 0 – 15 cm
2. Late June – early July: 0 – 30 cm
3. July – Aug: 0 – 90 cm
4. Sept – Oct (post-harvest): 0 – 90 cm

3.3.5. Plant root simulator (PRS®) nutrient supply measurement

Four pairs of PRS probes were installed in each plot at a depth of approximately 15 cm for a period of approximately three weeks to one month. Upon removal, the probes were collected and stored in sealed plastic bags, one for each plot, and refrigerated. Probes were cleaned with distilled water to remove soil particles and shipped to Western Ag Labs for analysis, along with bulk soil samples from each treatment for calibration.

3.3.6. Plant tissue sampling

Plant tissues were collected in late June/early July from 2021 to 2023. For wheat and oat crops, the flag leaf from 50 plants per plot were collected; for canola, the 5th leaf from the top of the plant without the petiole from 15 plants per plot were collected; and for soybean, the most recent, fully expanded trifoliate with petiole from 25 plants per plot. Samples were shipped within two days to Agvise Laboratories in Northwood, ND, USA where they were dried, ground and either digested and analyzed colorimetrically (for nitrogen) or burned and analyzed using an Inductively Coupled Plasma spectrophotometer (for phosphorus and potassium) as described in Jones et al. (1990).

3.3.7. Weed counts

Weeds were counted in 2021, 2022 and 2023 in late July/early August from four, 0.25 m^2 areas in each plot to arrive at weed counts per m^2, along with the breakdown of the various plant species observed. No weed counts were conducted in 2024.

3.3.8. Pre-harvest plant data

Plant height, head counts for wheat and stem counts for canola were conducted prior to harvest as supplemental information for crop biomass assessment.

3.3.9. Harvest data

Crops were harvested by hand from 2021 to 2024, taking one to three, 1-m^2 samples per plot as a subsample within each plot to address yield variability in the statistical analyses. Harvest samples were collected at BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemical Industry) phenological stages 87-92 for canola, oat, and wheat; and at BBCH stages 86-96 for soybean. Crop stages varied depending on site-year and landscape position) were placed in either cloth or jute bags and transported back to Agriculture and Agri-Food Canada, Portage la Prairie site where the samples were placed in a greenhouse to dry down. Approximately 2 weeks later, the samples were weighed for total biomass, harvested through a stationary Wintersteiger® plot combine and the grain samples collected and placed in a dryer at 60°C for approximately 24 hours to dry grain samples to a uniform moisture content. Grain samples were weighed, converted and reported for data analysis on a kg ha^{-1} basis. Yields were corrected to the standard moisture content for each crop type (14.5% moisture for wheat; 12.0% moisture for oat; 10.0% moisture for canola and 12.0% moisture for soybean).

3.3.10. Fall soil sampling for nutrient analysis and bulk density

Post-harvest soil samples were collected for nutrient analysis prior to freeze-up at all sites from 2021 to 2023. Due to equipment availability, only samples from Bruxelles were collected in fall, 2024. Sample collection was done using hydraulic, truck-mounted soil probes, depending on equipment availability. One probe had an inner diameter of 44 mm; the other had an inner diameter of 38 mm, which was noted and accounted for when calculating bulk density of samples collected in 2023 using these types of equipment.

Exchangeable ammonium and nitrate were extracted from soil with 2M KCl extract, filtered and analyzed using flow injection analysis (Kalra and Maynard, 1991; Maynard and Kalra, 1993). Olsen P was determined using a 0.5 M sodium bicarbonate extraction solution and measured using flow injection analysis as described by Olsen and Sommers (1982).

3.3.11. Canola strip trial at Bruxelles, 2023

Unbeknownst to the researchers until mid-season 2023, the landowner/producer of the Bruxelles site set up a field-scale canola variety strip trial with a local seed supplier that included the soil landscape restoration study area and caused concern over possible confounding of effects of topsoil addition and removal. Fortunately, the strips of different canola varieties had unique visual differences that made the researchers aware, so that the producer was contacted and confirmed this information with a map of the trial. The width of the variety strips was sufficient to include three of the four replicates (i.e., plots 1 and 2; plots 3 and 4; and plots 7 and 8) within the same canola variety. Only plots 5 and 6 were in separate strips and planted to different canola varieties. This was noted in case a random effect showed up as significant in the statistical analysis and this replicate could be discarded, if necessary.

3.3.12. Statistical analyses performed using R and SAS®

The field plots were set up as a Randomized Complete Block Design with four replicates of two treatments, each from two different landscape positions (control versus removed topsoil in the depressions; and control versus added topsoil on the knolls) from each of three field sites. Primary response variables were grain yield and total aboveground biomass (crop and weeds), with the following fixed effects: crop type (wheat, canola, oat, soybean), treatment (nested within landscape position), site and their interactions: site × treatment. Replicate was considered a random effect (nested within site). The SAS Glimmix model is a generalized linear mixed model based analysis that uses ANOVA and accommodates non-normal data that may also have unequal variances (Stroup, 2015). Repeated measures analysis using Generalized Linear Mixed Models in SAS® (SAS Online for Academics, SAS Institute, 2024; Stroup, 2015; Kesleman et al., 2016) were used in the ANOVA, with an $\alpha = 0.05$ to determine significant differences within fixed and random effects. A variety of co-variant structures were used based on the AIC value to support a better-fitting model. Means comparisons were conducted using the Tukey-Kramer method. Graphical depictions of selected data were constructed using R® software (version 4.4.1, R Core Team, 2024). All figures were created using the ggplot2 package (V3.3.3; Wickham, 2016).

Principle Component Analysis (PCA) was analyzed with OriginPro® software (Hearne Software, 2025) to produce a 3D graphical depiction of the relationships among eight measured variables: crop yield, total biomass, residual (fall) NH_4, NO_3 and PO_4; ^{137}Cs inventories, SOC stocks and available water in 30 cm of the soil profile. The cosine of the angle between variable vectors indicates the correlation strength among variables, with variable groupings arbitrarily based using an angle of 40° (i.e., r = 0.77; Hangs et al., 2025). Variable vectors pointing in the same direction represent direct relationships, opposing vectors indicate indirect relationships, and unrelated variables have vectors perpendicular to each other.

3.4. Results

Results are primarily focused on the crop responses (biomass and yield) to added and removed topsoil versus control plots, with weather data, soil moisture and fertility data presented to provide clues to explain the limited crop responses by site-year. Prior to running the final model, assumptions of ANOVA were tested using Gaussian distribution of residuals and homogeneity of variances, where it was determined no corrections were needed. Multivariate analysis (PCA) will attempt to measure correlations among variables to better explain any interactions among the data.

3.4.1. Weather data by site

Growing Degree Days (GDD) over the May 1 – September 30 growing seasons (Table 2) during the study period was generally warmer than historical values, with the exceptions of Manitou in 2022 (96% of normal) and Bruxelles in 2024 (90% of normal). Precipitation values over that same period were generally lower than historical values, especially in the drought years 2021 and 2023. However, above normal precipitation values were received at Bruxelles in 2022 (112% of normal), with most of the precipitation received during the months of May and July. In 2024, all sites received higher than historical precipitation (108 – 136% of normal), with the bulk of it received in the months of May and June.

Table 3. 2. Weather data over study period by site.

May -Sept	Growing Degree Days (% of historical)					Precipitation (mm) (% of historical)				
	Historical	2021	2022	2023	2024	Historical	2021	2022	2023	2024
Altamont	1671	1945 (116)	1762 (105)	1962 (117)	1853 (111)	345	281 (81)	291 (84)	162 (47)	421 (122)
Bruxelles	1671	1752 (105)	1709 (102)	1892 (113)	1498 (90)	345	N/A	386 (112)	203 (59)	373 (108)
Manitou	1674	1725 (103)	1602 (96)	1798 (107)	1678 (100)	340	250 (74)	312 (92)	196 (58)	463 (136)

3.4.2. Harvest data

3.4.2.1. Landscape effects

All sites exhibited significant landscape effects in which biomass (Figure 3.1) and grain yields (Figure 3.2) in the depressions were greater than those on the knolls. All sites had relatively low, but also highly variable, biomass and yields relative to corresponding values from their depressions. The knolls at the Bruxelles site had biomass 43 – 92% of values found in the depressions and crop yields on knolls were 44 – 90% of yields in the depressions. At Manitou, these differences in relative crop performance by landscape position were more variable than at Bruxelles but improved considerably over time, from 11% for biomass in 2021 to 92% in 2024; and from 0% for grain yield in 2021 to 79% in 2024, due to the return of adequate precipitation. However, at Altamont, depressions were subject to excess moisture conditions from underground springs and side-hill seeps observed under prolonged wet conditions that would result in occasional reversals of the landscape effect, where the biomass (2021) or the yield (2022 and 2023) would be greater on the knoll than in the depression. This would produce relative productivity ratios considerably larger than 100%, which are generally considered impractical for interpretations.

In terms of improving overall crop productivity in the landscape, the goal was to increase relative grain yields of knoll versus depression from 30 – 50% to a relative productivity of 70 – 80% (Zymouya, personal communication). Without soil landscape restoration, relative crop productivity of the control knolls versus the control depressions (CK divided by CD) ranged from 75 – 175% for biomass and 24 - 255% for grain yield at Altamont; from 43 – 59% for biomass and 44 - 55% for grain yield at Bruxelles; and from 14 - 92% for biomass and 0 – 78% for grain yield at Manitou. When soil landscape restoration treatments were applied, relative crop productivity of the added knolls as a percentage of the removed depression (AK divided by RD) increased numerically for biomass and grain yield for all sites in at least three of the four growing seasons. Although only 4 of the 12 site-years were determined to be statistically significant increase in grain yield from added topsoil, 7 of 12 site-years exceeded the relative crop productivity target of >70% numerically, suggesting the need for more site-years of data, additional management practices in addition to soil landscape restoration or more statistical power in the data analyses.

Table 3. 3. Total crop biomass (kg ha^{-1}) by site and treatment.

Site Year	Crop	Control Depression (CD)	Removed Depression (RD)	% Change	Control Knoll (CK)	Added Knoll (AK)	% Change	CK÷CD %	AK÷RD %
				Altamont					
2021	Wheat	4400	2400	- 45*	7700	9400	+22*	175	392
2022	Canola	11600	10900	-6	8700	9100	+5	75	83
2023	Wheat	3900	4600	+18	3000	2900	-3	77	63
2024	Canola	4500	2500	-44*	5100	4000	-22	113	160
				Bruxelles					
2021	Wheat	6200	6300	+2	2900	4200	+45	47	67
2022	Oat	6800	7500	+10	4000	3900	-3	59	52
2023	Canola	8600	6500	-24	3700	3600	-3	43	55
2024	Wheat	12700	11000	-13	7100	10100	+42*	56	92
				Manitou					
2021	Canola	9200	8900	-3	1300	1000	-23	14	11
2022	Soybean	6700	6300	-6	1800	2100	+17	27	33
2023	Wheat	6300	5900	-6	2400	2400	0	38	41
2024	Canola	7700	8000	+4	7100	7200	+1	92	90

P value for site × treatment × year effect = 0.0001 (* = significant at α = 0.05)

Table 3. 4. Crop yields (kg ha^{-1}) by site and treatment.

Site Year	Crop	Control Depression (CD)	Removed Depression (RD)	% Change	Control Knoll (CK)	Added Knoll (AK)	% Change	CK÷CD %	AK÷RD %
				Altamont					
2021	Wheat	3640	2370	- 35*	860	810	-8	24	34
2022	Canola	590	70	-90*	1550	1910	+21*	255	340
2023	Wheat	1460	1300	-14	750	1010	+15	59	79
2024	Canola	1100	260	-75*	1200	1260	+5	105	440
				Bruxelles					
2021	Wheat	3700	2630	-29*	1640	1160	-29	44	44
2022	Oat	4950	4360	-12	2730	4110	+50*	55	94
2023	Canola	2010	1980	-3	1060	1590	+47*	53	80
2024	Wheat	5590	4680	-16	2670	4230	+58*	48	90
				Manitou					
2021	Canola	1120	1440	+30	40	40	0	0	0
2022	Soybean	3960	3890	-2	930	1130	+21	24	29
2023	Wheat	3310	2990	-10	1010	1240	+20	31	41
2024	Canola	2540	2380	-7	1960	1840	-6	78	79

P value for site × treatment × year effect = 0.0001 (* = significant at $\alpha = 0.05$)

3.4.2.2. Treatment effect - topsoil removal from depressions

Removal of topsoil resulted in significant reductions of approximately 45% in total biomass in two site-years (Altamont in 2021 and 2024) when compared to the control depression. A significant negative crop yield response was observed when topsoil was removed from depressions in four site-years (Altamont in 2021, 2022 and 2024; Bruxelles in 2021). Yield reductions ranged from 35 – 90% at Altamont and 29% at Bruxelles.

The treatment effect of removing topsoil from the depression, resulting in a significant negative response in biomass and/or yield occurred at Altamont in three out of four growing seasons, was due to crop drowning out where water was transmitted through the upper parts of the landscape and to lower parts of the landscape where water was retained, especially in areas of removed topsoil. The lower frequency of standing water at the Bruxelles and Manitou sites was the result of better internal drainage in the depressions of these sites (either naturally or as improvements by humans, respectively), as well as the absence of large precipitation events throughout most of the study period.

3.4.2.3. Treatment effect - topsoil addition to knolls

Significant, positive crop yield responses, when topsoil was added to knolls and compared to the control knoll, occurred in four site-years but not necessarily in the same site-years as for the removed topsoil response (Altamont in 2022; Bruxelles in 2022, 2023 and 2024). Significant biomass increases were 22% at Altamont in 2021 and 42% at Bruxelles in 2024. No significant differences in either yield or biomass were observed at Manitou. Yield increases from added topsoil were 21% at Altamont in 2022 and ranged from 47 – 58% at Bruxelles over three years (Figures 3.1 and 3.2). One replicate was removed from Bruxelles yield analysis in 2023 due to a confounding effect, but this still produced a significant treatment effect.

Treatment effects from the removal of topsoil (in the depression) produced significant, negative effects in reduced biomass in two of 12 site-years and reduced grain yields in four of 12 site-years (three of which were at Altamont). Treatment effects from the addition of topsoil to the knoll produced significant, positive differences in crop productivity (2 of 12 site-years for biomass; 4 of 12 site-years for yield), three of which were at Bruxelles, which also displayed significant increases in ^{137}Cs and SOC from added topsoil, as described in Chapter 2.

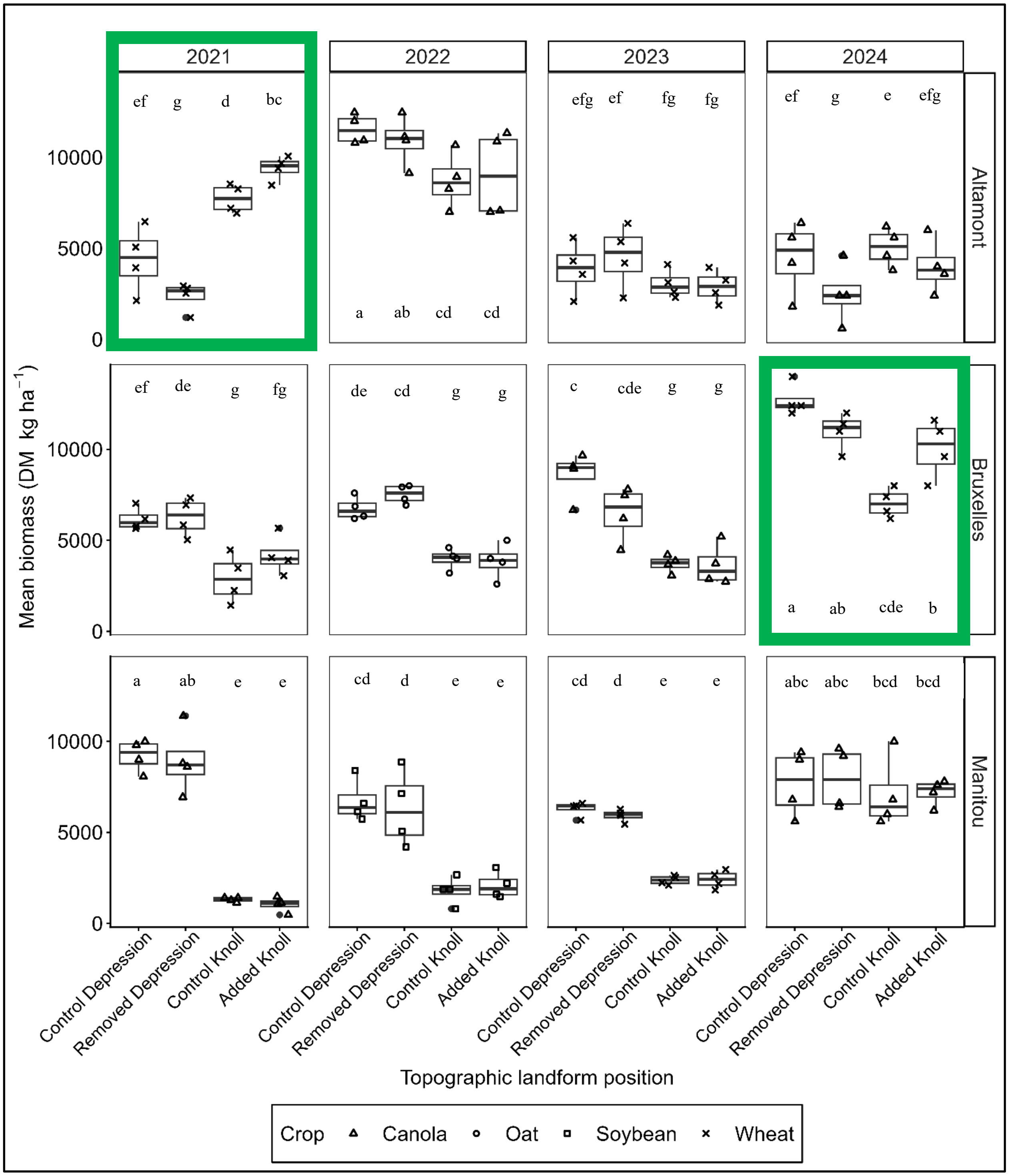

Figure 3. 1. Boxplot distributions of total biomass by crop, treatment and site (2021-2024). Site-years highlighted in green are significant responses to added topsoil on the knolls. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at $\alpha = 0.05$.

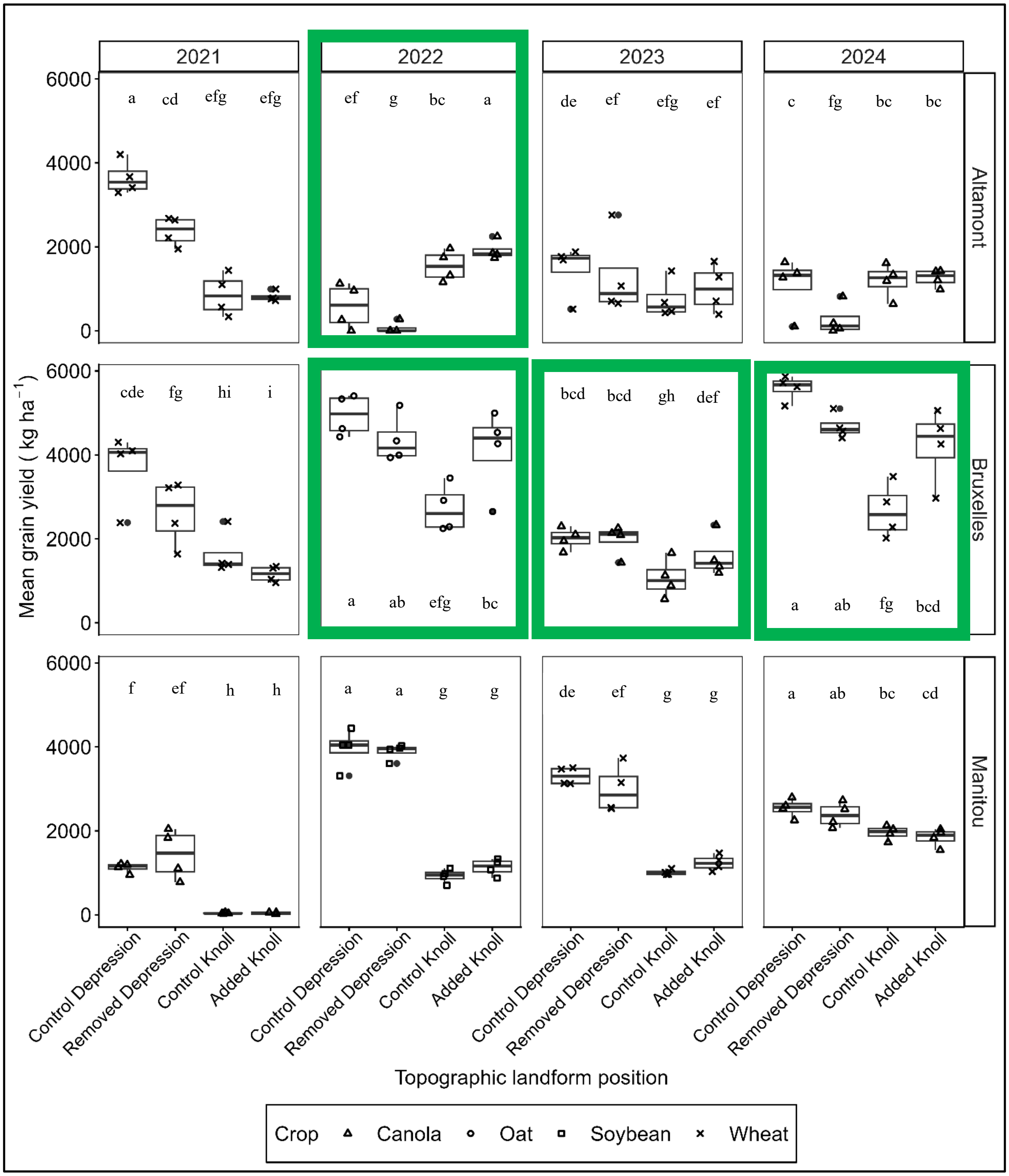

Figure 3. 2. Boxplot distributions of crop yields by crop and site (2021-2024). Site-years highlighted in green are significant treatment responses to added topsoil on the knolls. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05.

3.4.3. Seedling emergence counts

Figure 3.3 examines the plant densities after full emergence in spring at each of the sites from 2021 to 2023. Target plant populations are 250 plants m^{-2} for spring wheat and oats (Manitoba Agriculture, 2025), 80 plants m^{-2} for canola (Canola Council of Canada, 2025) and 40 soybean plants m^{-2} (Manitoba Pulse and Soybean Growers, 2025). In terms of site effects, Altamont had plant populations of wheat and canola below target levels, whereas Bruxelles plant populations for these crops were numerically higher than the other sites, which may explain some of the difference in crop response between these two sites. The Altamont site also experienced higher weed pressure (see section 3.4.8) than the other sites, which would further reduce crop stands and crop performance.

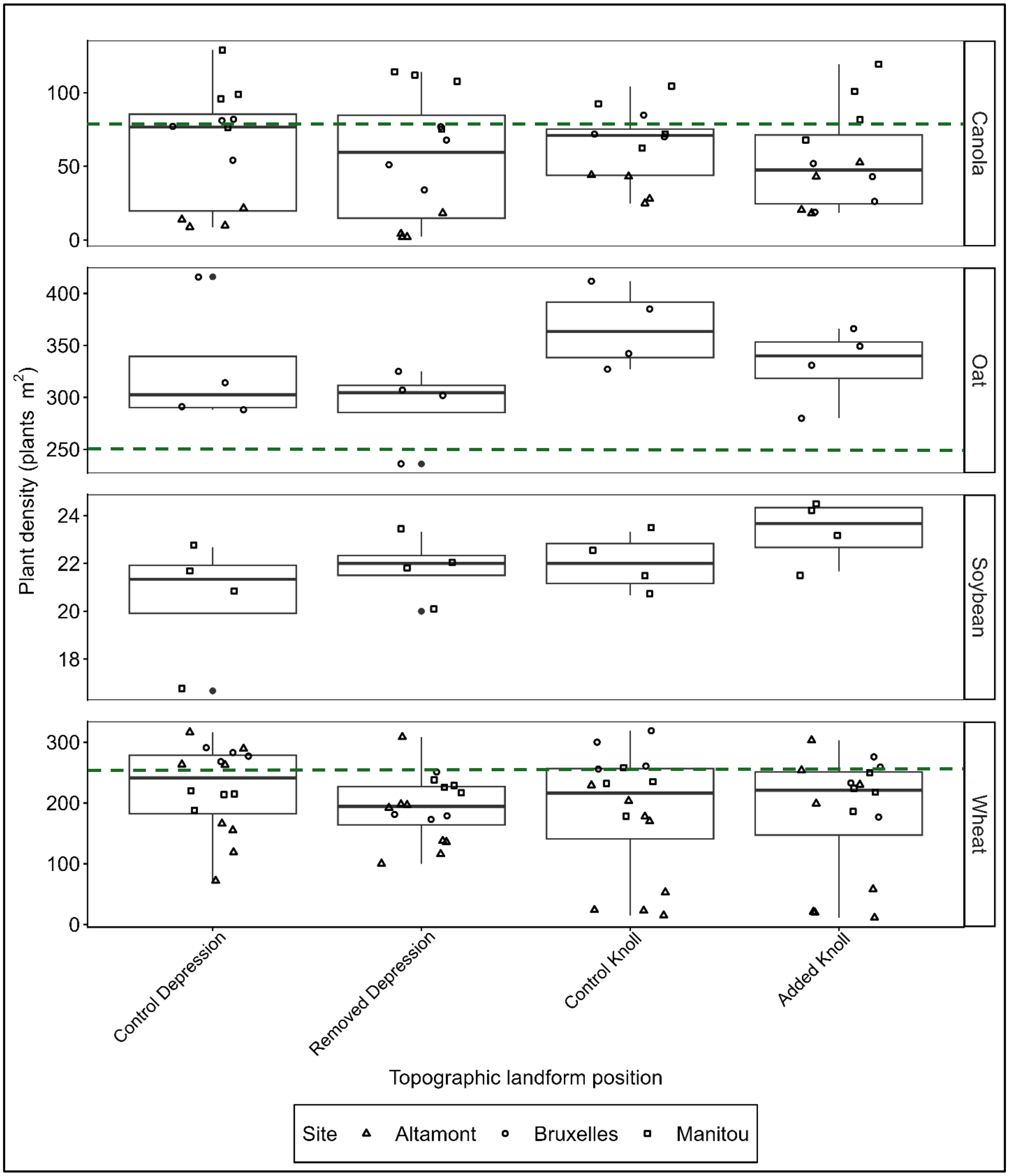

Figure 3. 3. Boxplot distributions of plant counts by crop type, treatment and site (2021-2023). No plant count data for 2024. The dashed green line is the target plant stand for each crop; all soybean populations were below the target population of 40 plants m^{-2}. There were 4 site-years of wheat; 3 site-years of canola and 1 site-year each of oat and soybean.

3.4.4. Total soil water by site

3.4.4.1. Altamont

The landscape effects at this site often displayed higher soil moisture on knolls than in depressions during the fall seasons of 2021 and 2023 (Figures 3.4, 3.5 and 3.6). Total water range for the 0-90 cm depth for this site was highly variable by year: 200 – 300 mm in 2021, 300 - 350 mm in 2022 and 250 – 350 mm in 2023. More soil water in the knoll position than in the depression, especially after harvest, was likely due to the presence of weeds in the depression continuing to utilize soil moisture into the fall. Treatment effects in the depression were the consistently higher soil moisture in the control depression rather than the removed topsoil treatments throughout 2022 and 2023, despite the removed depressions serving as a potential artifact for water ponding. Adding topsoil to the knoll at this site did not increase soil water over the control.

3.4.4.2. Bruxelles

Coarser materials in the soils at Bruxelles resulted in lower total water stored than in Altamont soils with range of total water from 150 – 225 (up to 250 mm in 2022) in the three years measured. In terms of landscape effects, the knolls were consistently drier than depressions, but with only slight differences in the wetter growing season of 2022. No appreciable treatment effects were observed in the depression due to the removal of topsoil. This can be partially explained by having a well-drained soil (Dezwood series) as a factor in reducing the risk of localized ponding of water after significant rainfall events. Adding topsoil to the knoll increased soil water throughout the 2022 growing season but to a lesser degree in 2021 or 2023 when precipitation and soil moisture were more limited.

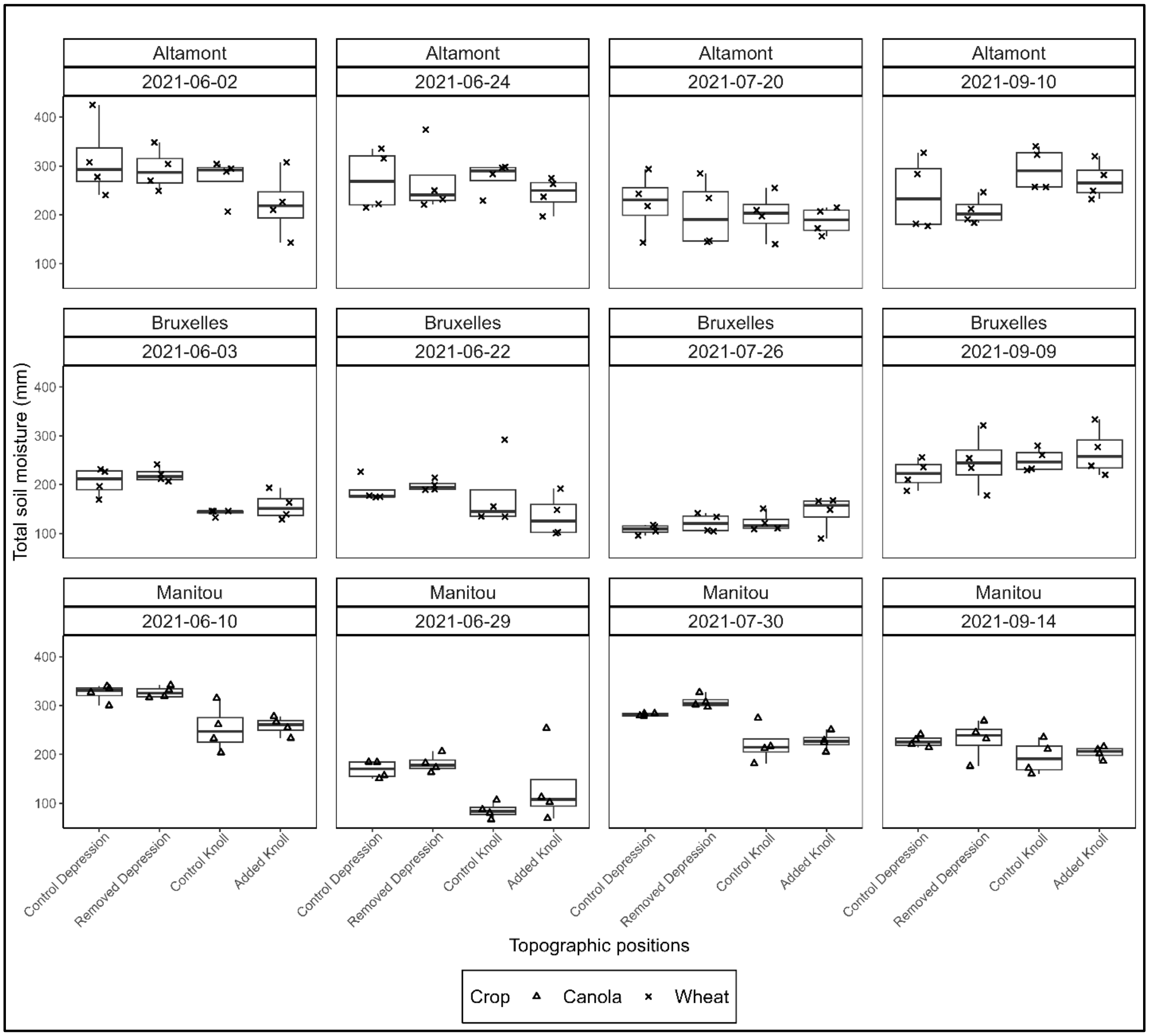

Figure 3. 4. Total soil water to 90 cm depth for 2021, by site and by treatment, over four sampling dates throughout the growing season.

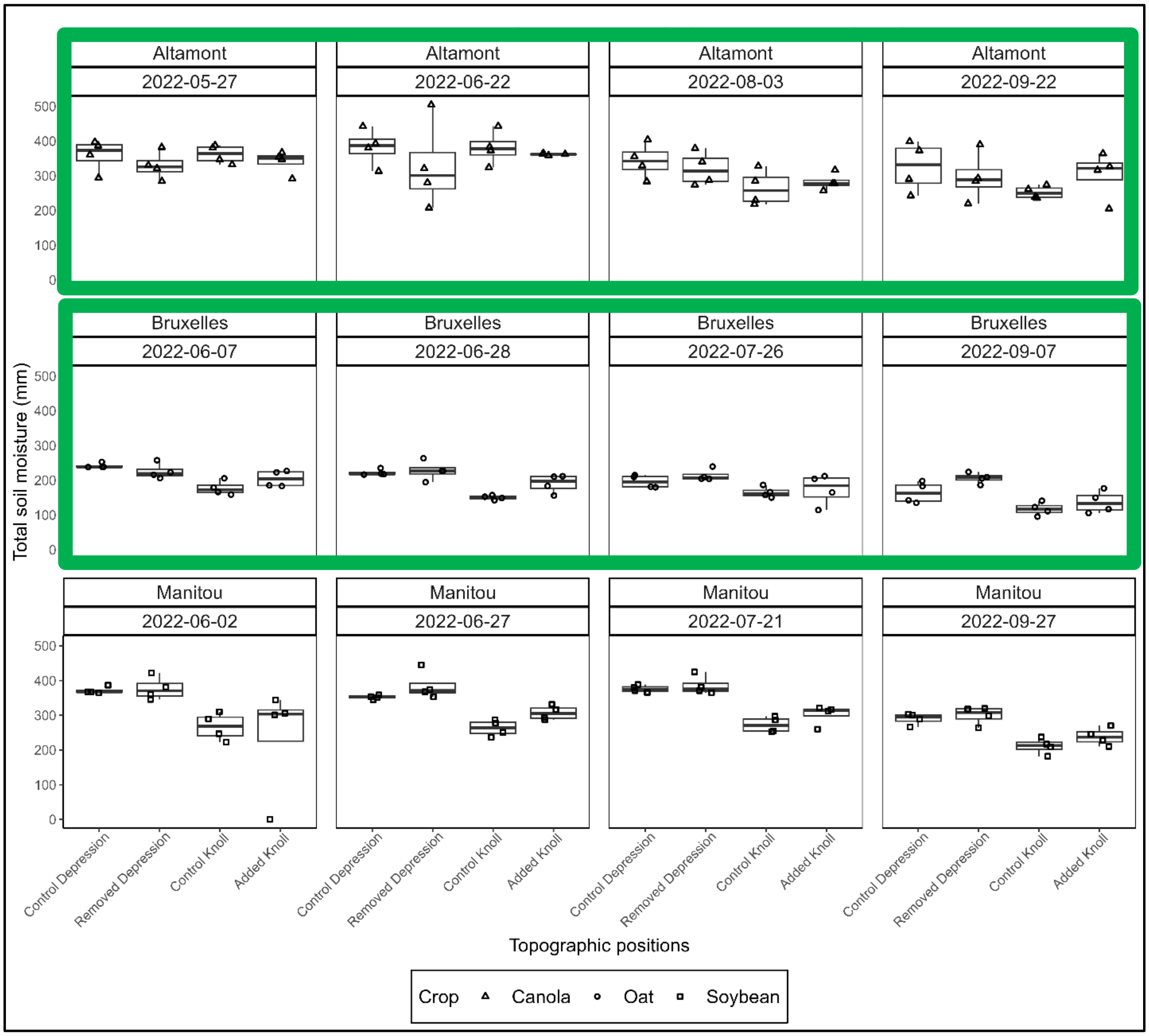

Figure 3. 5. Boxplot distributions of total soil water to 90 cm depth for 2022, by site and by treatment, over four sampling dates throughout the growing season. Site-years highlighted in green are significant crop yield responses to added topsoil.

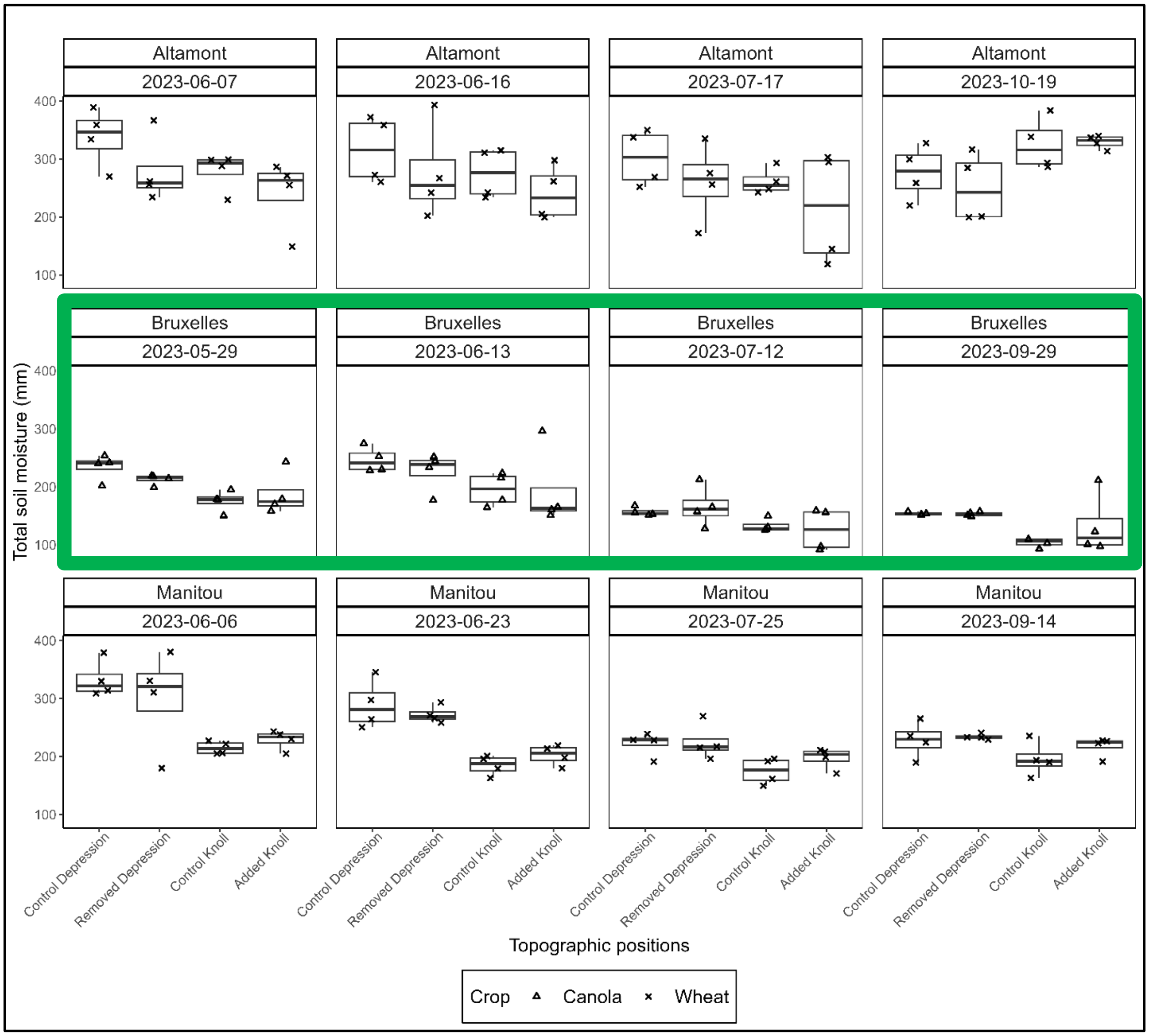

Figure 3. 6. Boxplot distributions of total soil water to 90 cm depth for 2023, by site and by treatment, over four sampling dates throughout the growing season. Site-years highlighted in green are significant crop yield responses to added topsoil.

3.4.4.3. Manitou

Different landscape positions produced contrasting levels of total soil moisture, with depressions consistently wetter than knolls throughout the dry 2021 growing season, until post- harvest, when the difference narrowed substantially (range 100 – 325 mm). These landscape differences continued in 2022 (range 250 – 400 mm) but were less pronounced over the growing season than in 2021. The year 2023 was another dry year at Manitou, with a total soil water range of 175 – 325 mm. The large difference in soil water between depression and knoll narrowed over time in the 2023 growing season. Only minor, occasional treatment effects were observed in the depression, but increased soil water values due to added topsoil were observed on the knoll.

3.4.5. Available water (AW)

In Chapter 2, adding topsoil to eroded knolls produced a range of responses for SOC stocks when compared to the control knoll, according to site. SOC stocks increased significantly at Bruxelles, increased only numerically at Manitou and essentially did not increase at Altamont. Given the effect increasing SOC is expected to have on increasing AWHC, similar outcomes for the three sites are expected.

Analysis of soil moisture using AWHC was determined using critical moisture retention parameters, field capacity (FC) and permanent wilting point (PWP), as shown in Table 3.5, along with sampling dates tracked over 3 growing seasons (Figures 3.7, 3.8 and 3.9). When plant-available water and rooting depth limitations are considered, the landscape and treatment differences become less apparent than when observing total water, but it also depicts longer periods of time when AW was limiting in the early part of the growing season.

Analysis of variance of the AWHC of the samples from 0-5 cm depth found no significant differences among treatments ($P = 0.2692$), a significant difference among sites ($P = 0.0238$), with samples from Manitou having higher AWHC than samples from Bruxelles and no significant site × treatment interaction (P = 0.2565). In addition, ANOVA of bulk densities of these 0-5 cm samples (BD, g cm^{-3}) revealed no significant treatment effect (P = 0.0889); a significant site effect (P < 0.0001) where Bruxelles samples had significantly increased bulk densities compared with samples from Altamont and significantly higher than samples from Manitou; yet no significant site × treatment effect was detected (P = 0.8193). Though generalized and based on a limited number of samples, relative changes in AWHC capacity through the addition of topsoil are positive for the Bruxelles site, negligible for the Manitou site and negative for the Altamont site.

Table 3. 5. Critical moisture parameters (by % volume) by site at near-surface depths (cm) – from Table 4.8 (2024). (Number of samples = 12)

		Control Knoll (CK)			Added Knoll (AK) (from Control Depression)			
Site	Depth (cm)	FC	PWP	AWHC (CK)	FC	PWP	AWHC (AK)	AWHC (AK – CK) (%)
Altamont		Poyser series			Tellier series			
	0-15	43.9	20.1	23.8	43.1	21.0	22.1	-1.7 (-7.2)
	15-25	38.2	18.5	19.7	38.9	21.5	17.4	-2.3 (-11.7)
Bruxelles		Vandal series			Dezwood series			
	0-15	31.4	14.9	16.5	36.0	18.0	18.0	1.5 (9.1)
	15-25	27.7	14.6	13.1	32.0	16.4	15.6	2.5 (19.1)
Manitou		Fifere series			Guerra series			
	0-15	41.4	25.4	16.0	42.5	24.7	17.8	1.8 (11.3)
	15-25	40.4	24.0	16.4	43.7	28.5	15.2	-1.2 (-7.3)

FC = Field Capacity
PWP = Permanent Wilting Point
AWHC = Available Water Holding Capacity

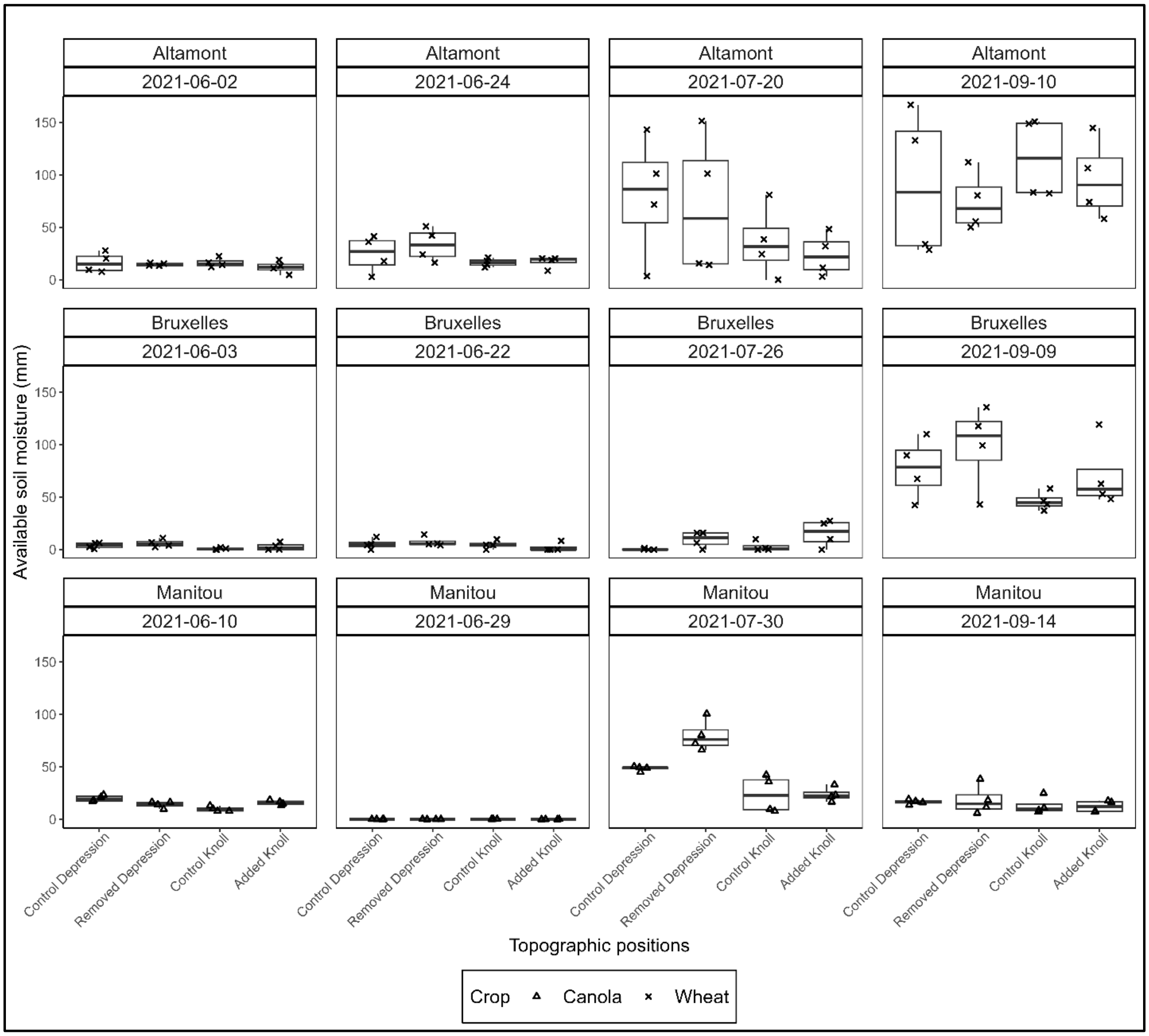

Figure 3. 7. Boxplot distributions of available soil water to 90 cm depth for 2021, by site and by treatment, over four sampling dates throughout the growing season.

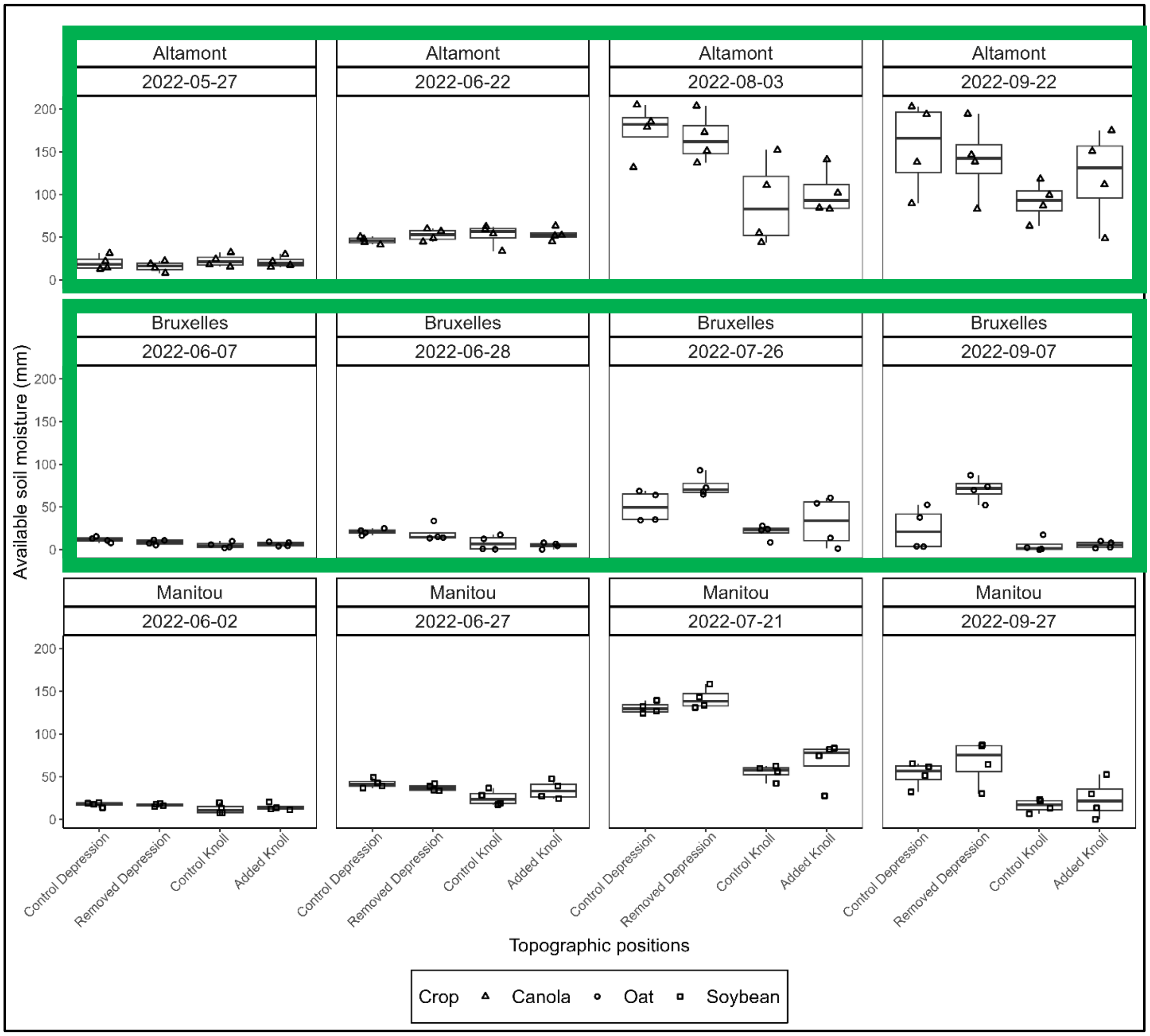

Figure 3. 8. Boxplot distributions of available soil water to 90 cm depth for 2022, by site and by treatment, over four sampling dates throughout the growing season. Site-years highlighted in green are significant crop yield responses to added topsoil.

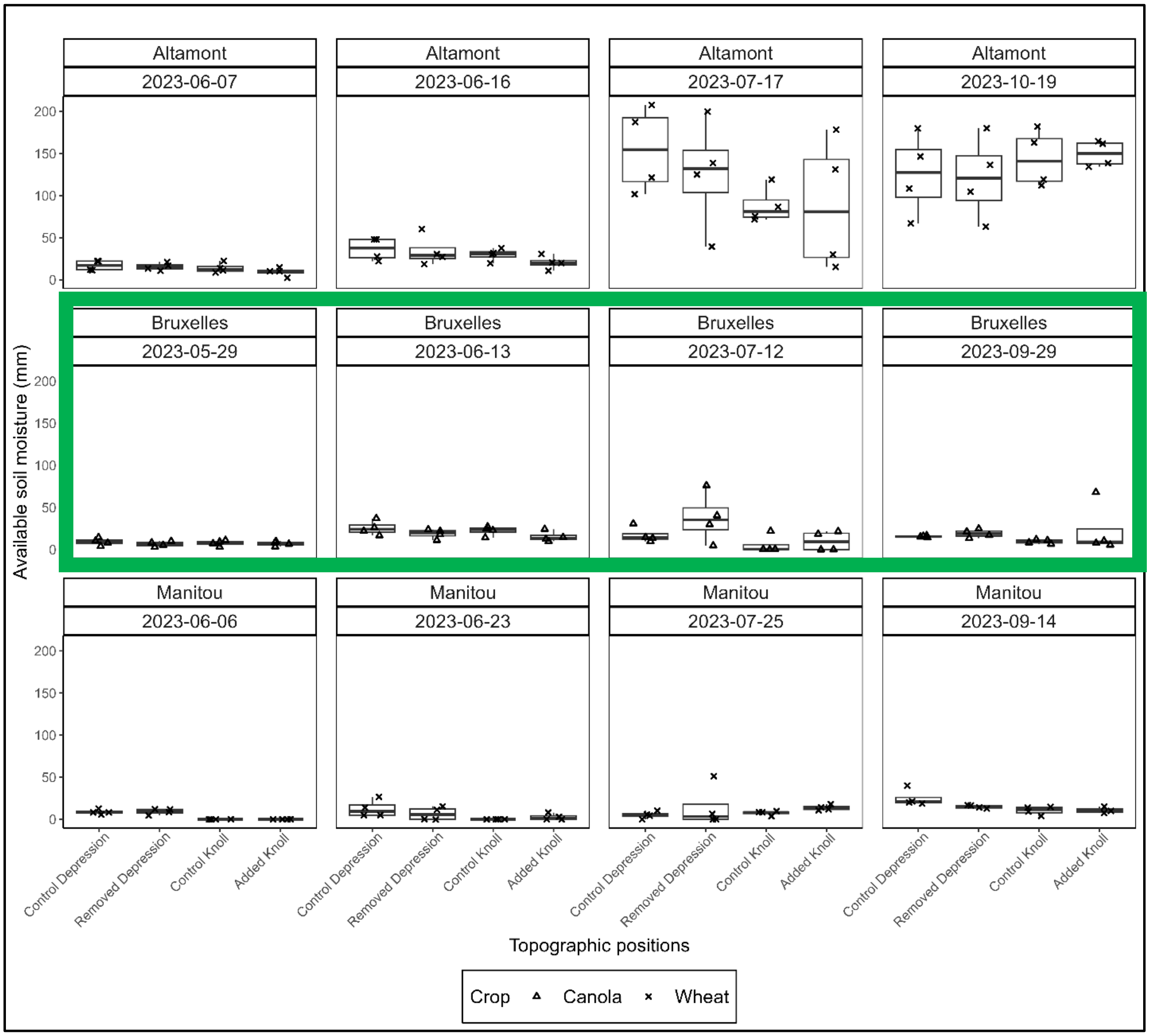

Figure 3. 9. Boxplot distributions of available soil water to 90 cm depth for 2023, by site and by treatment, over four sampling dates throughout the growing season. Site-years highlighted in green are significant crop yield responses to added topsoil.

3.4.6. PRS probes

Nitrogen and phosphorus supply rates did not significantly increase in the site-years where crop yields responded significantly to added topsoil (Figures 3.10 and 3.11). A lack of soil moisture was the driving factor in determining crop response, based on below-normal precipitation in 2021 and 2022 at Altamont and in 2021 and 2023 at Manitou. A history of manure application prior to the 1990's may explain some of these values on the knolls at Manitou. To a lesser extent, there were influences on N and P supplies by treatments, in that removing topsoil may temporarily reduce nutrient supplies and adding topsoil would increase supplies, but this would be overcome by annual fertilization practices by the producer.

Qian and Schoenau (2005) assigned an approximate nitrogen supply range for Black Chernozemic soils of 1100 – 1500 µg nitrate-N 10 cm^{-2} per 2 weeks of incubation. Eroded soils were approximately 55% of their non-eroded counterparts (Dark Brown Chernozemic soils). Nitrogen supply rates for the three sites in this study were considerably less than those reported for Black soils in Qian and Schoenau (2005) even though the incubation period was longer. Phosphorus supply rates for these sites were higher than those reported by McAuley et al. (2025) near Saskatoon, SK. Rates were approximately 2 – 4 µg 10 cm^{-2} per 2.5 weeks of incubation in a dry year (2021) and approximately 10 – 15 µg 10 cm^{-2} per 4 weeks of incubation in an average year (2022).

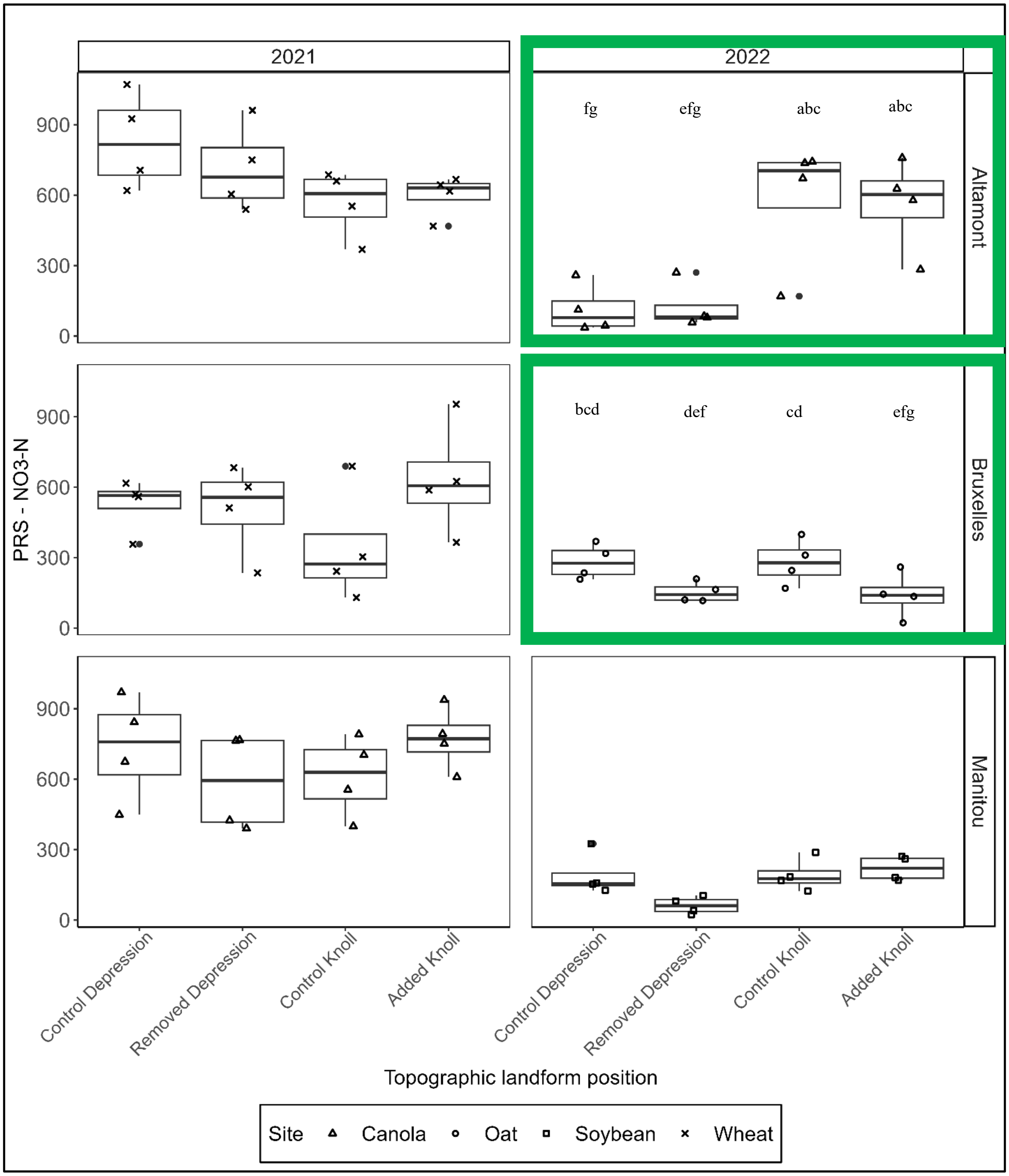

Figure 3. 10. Boxplot distributions of Plant Root Simulator probe nutrient supply (µg 10 cm^{-2} (burial length)$^{-1}$) for NO_3^--N by crop, year, treatment and site. Site-years highlighted in green are significant crop yield responses to added topsoil. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05.

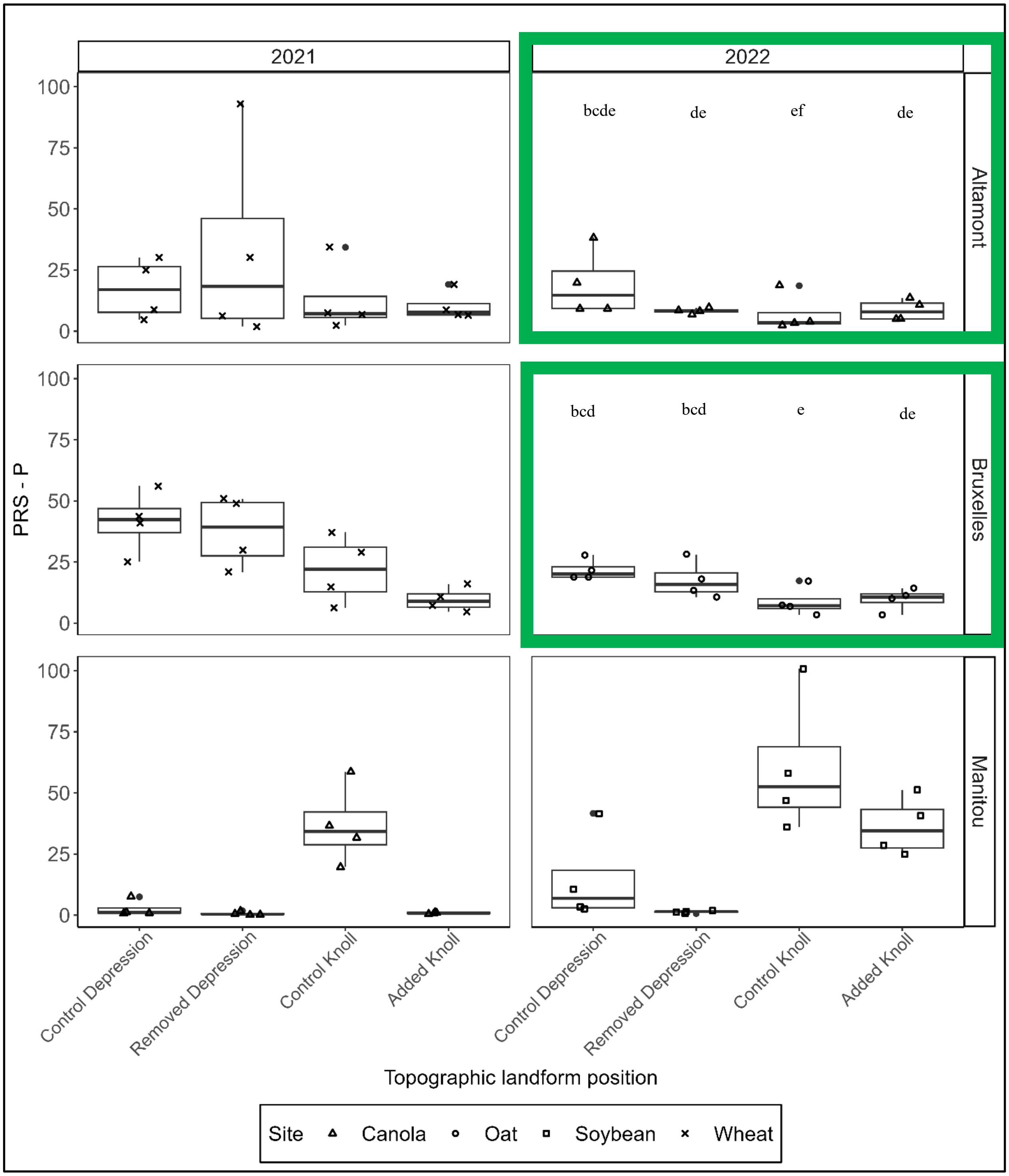

Figure 3. 11. Boxplot distributions of Plant Root Simulator probe nutrient supply (µg 10 cm^{-2} (burial length)$^{-1}$) for phosphorus by crop, year, treatment and site. Site-years highlighted in green are significant crop yield responses to added topsoil. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at $\alpha = 0.05$.

3.4.7. Plant tissue tests

Generally, mean plant shoot tissue test values for macronutrients N and P (Figures 3.12 and 3.13) fell within standard sufficiency ranges, though some data points would be considered marginal or low for P and K at Bruxelles (see Figures B2 and B3 in Appendices), due to the sandy texture of the soil profile on the knoll at Bruxelles. This suggests nutrient uptake by the plants was limited due to a lack of moisture in some of the responsive site-years. No macronutrients were in the deficient range for any of the site-years.

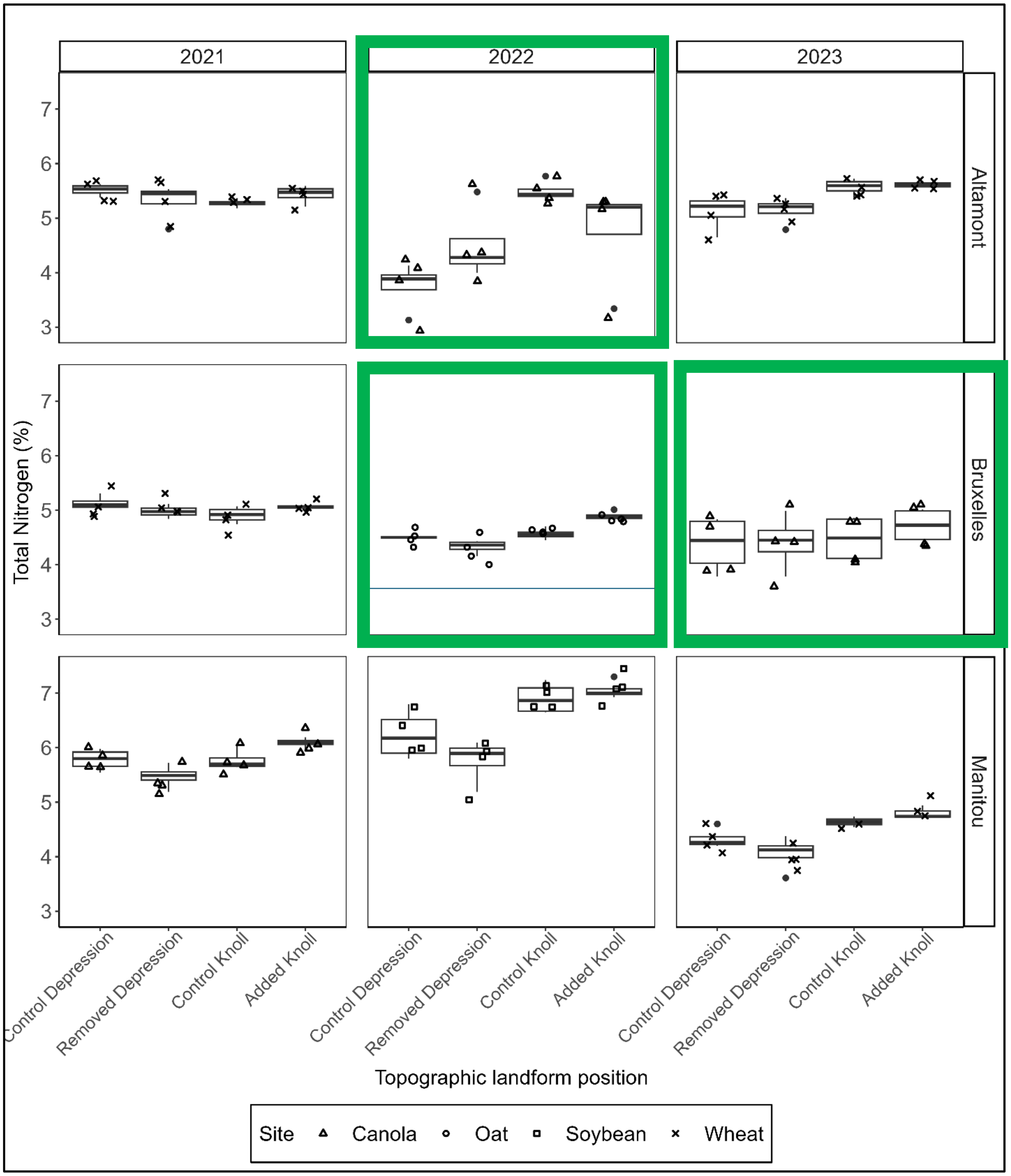

Figure 3. 12. Boxplot distributions of plant tissue tests for total nitrogen (%) by year, site, treatment and crop. Site-years highlighted in green are significant crop yield responses to added topsoil.

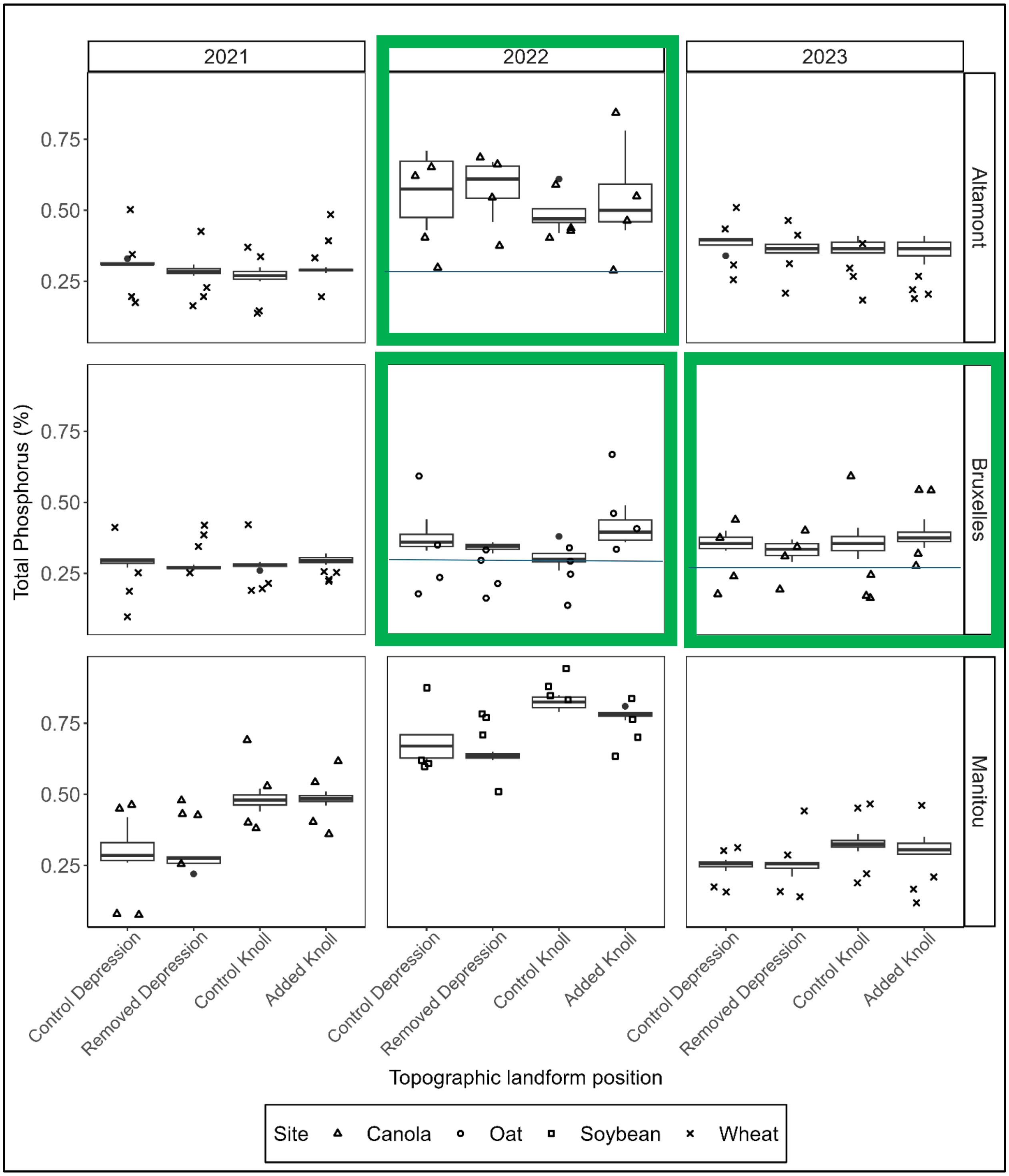

Figure 3. 13. Boxplot distributions of plant tissue tests for total phosphorus (%) by year, site, treatment and crop. Site-years highlighted in green are significant crop yield responses to added topsoil.

3.4.8. Weed counts

Weed counts following in-crop herbicide applications in all years for the three sites did not produce a significant treatment effect ($P = 0.1115$) but did produce a significant site effect ($P < 0.0001$), year effect ($P = 0.0377$), site × year interaction ($P = 0.0277$) and site × treatment interaction ($P < 0.0001$). The Altamont site exhibited significantly high weed pressure throughout the study period with mean counts greater than 250 plants m^{-2}, followed by the Bruxelles site with less than 100 plants m^{-2} and even fewer weeds at the Manitou site (1 plant m^{-2}). In 2021, the Altamont site had high populations of Stork's bill (*Erodium cicutarium*, L.) on the control knoll but were buried by added topsoil. Foxtail species (*Setaria* spp, L.) and smartweed (*Persicaria pensylvanica*, L.) were also in abundance. In 2022, weeds populations were more uniform across treatments with greater species diversity than in 2021. For 2023, weed populations increased in depressions dominated by foxtail and barnyard grass (*Echinochloa crus-galli*, L.).

High populations of foxtail species and Stork's bill populations were present at Bruxelles in 2021. In 2022, weed populations were greater on knoll treatments than depressions, with foxtail as the dominant weed. In 2023, weed populations were dominantly foxtail species, increasing on the knolls and declining in the depressions.

Table 3. 6. Mean weed populations (plants m-2) by treatment and by year at three soil landscape restoration sites. Different letters following weed counts represent significant differences. Site effect (P < 0.001), year (P = 0.0377), treatment effect (P = 0.1115), site × year interaction (P = 0.0277) and site × treatment interaction (P < 0.0001).

Site ($P < 0.0001$)	Year ($P = 0.0377$)	Treatment ($P = 0.1115$)			
		Control Depression	Removed Depression	Control Knoll	Added Knoll
Altamont a	2021 a	141	79	672	54
	2022 ab	234	292	264	87
	2023 a	409	577	158	196
Bruxelles b	2021 bc	4	7	326	21
	2022 bc	14	39	267	97
	2023 c	22	54	130	82
Manitou c	2021 e	1	0	1	0
	2022 d	3	7	1	0
	2023 e	0	0	0	0

3.4.9. Fall soil nutrient status

Figures 3.14 and 3.15 depict post-harvest nitrate-N and Olsen P at various depths, across landscape positions and treatments and by site, from fall, 2021 to fall, 2023. Generally, residual NO_3^--N concentrations were significantly greater for the added knoll treatment than the control knoll at nearly all depths. Additionally, residual NO_3^--N concentrations were significantly lower in the removed depression treatment than the control depression treatment at the two surface depths. This suggests that NO_3^--N was transported upslope with the addition of topsoil. P values for site effect at all depths were $P < 0.0001$. For the treatment effect, significant P values at all depths were $P = 0.0020$ (0-5 cm), $P < 0.0001$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P = 0.0017$ (30-60 cm) and $P = 0.0360$ (60-90 cm). P values for site × treatment interactions by depth were $P = 0.0093$ (0-5 cm), $P = 0.1698$ (5-15 cm), $P = 0.5484$ (15-30 cm), $P = 0.2746$ (30-60 cm) and $P = 0.0385$ (60-90 cm). Significant site × treatment interactions were at the 0-5 cm and 60-90 cm depths only.

Similarly, Olsen P concentrations decreased with depth, with a significant reduction in P concentration in the removed depression treatment versus other treatments at 0-5 cm and 5-15 cm depths. Although P concentrations vary among sites and treatments, they are not significantly different nor yield-limiting to crops. P values for site effect by depth were $P = 0.1206$ (0-5 cm), $P = 0.0031$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P < 0.0001$ (30-60 cm) and $P < 0.0001$ (60-90 cm). For the treatment effect, P values by depth were $P = 0.1339$ (0-5 cm), $P < 0.0001$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P < 0.0001$ (30-60 cm) and $P = 0.0003$ (60-90 cm). P values for the site × treatment interaction by depth were $P = 0.0013$ (0-5 cm), $P < 0.0001$ (5-15 cm), $P < 0.0001$ (15-30 cm), $P < 0.0001$ (30-60 cm) and $P < 0.0001$ (60-90 cm), significant at all depths. All three sites had P fertilizer regularly applied, though it was sometimes broadcast at the Altamont site.

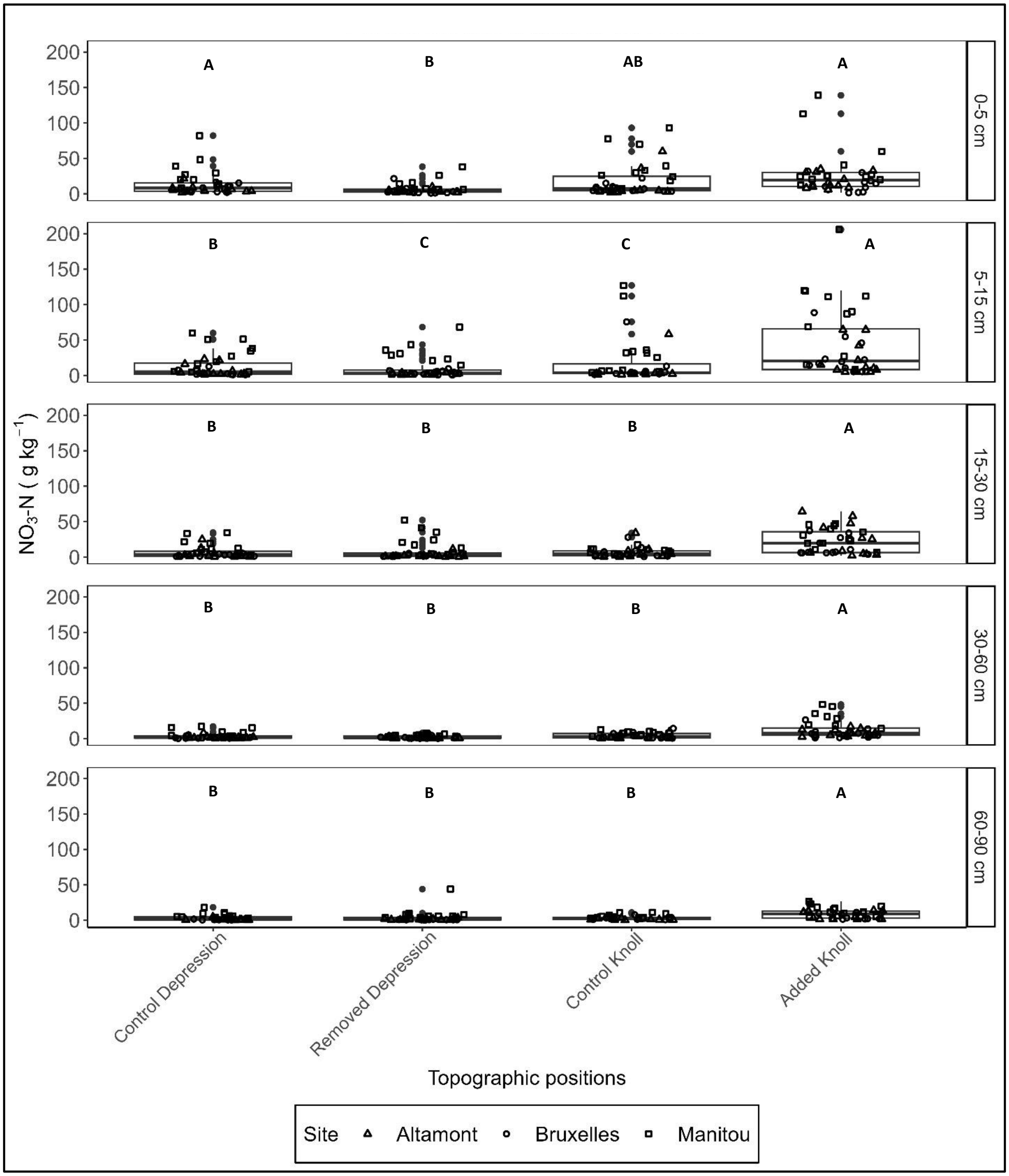

Figure 3. 14. Boxplot distributions of fall soil test NO_3-N (g kg^{-1}), by depth, topographic position and treatment (all sites). Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α= 0.05

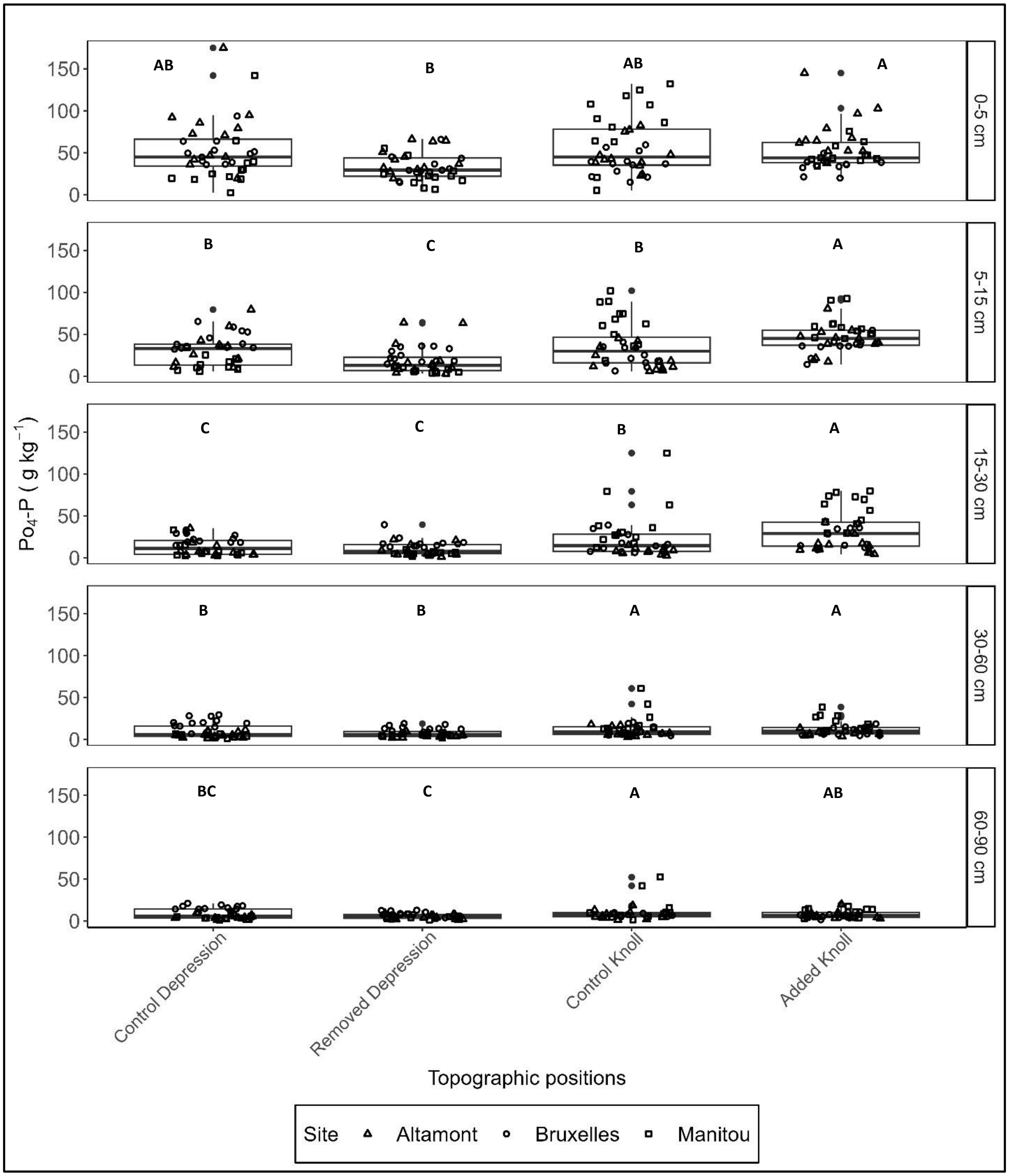

Figure 3. 15. Boxplot distributions of fall soil test Olsen P (g kg^{-1}), by depth, topographic position and treatment (all sites). Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05.

3.4.10. Principal component analysis

The first two principal axes (Figure 3.16) accounted for approximately 47% of the total variation. PC1 explained approximately 30% of the variance, primarily driven by crop yield and biomass. PC2 contributed approximately 18% to the total variance and was strongly influenced by total soil moisture in the profile and SOC stocks. PC3 explained another 16% of the total variance. Crop factors (yield and biomass) were normalized by crop type according to highest yield achieved. Yield and biomass were strongly correlated to each other, but not strongly to other components, with the possible exception of ^{137}Cs inventories. Soil moisture (total soil moisture in the entire 90 cm soil profile) was positively correlated with SOC stocks and negatively correlated to residual fall PO_4. Eigenvalues of the vectors (Figure 3.17) showed five principal components greater than 1.0, suggesting that there are multiple independent drivers of crop response, not just one or two dominant ones. This is why the PCA was presented in three dimensions rather than two (see Figure B5 in appendices).

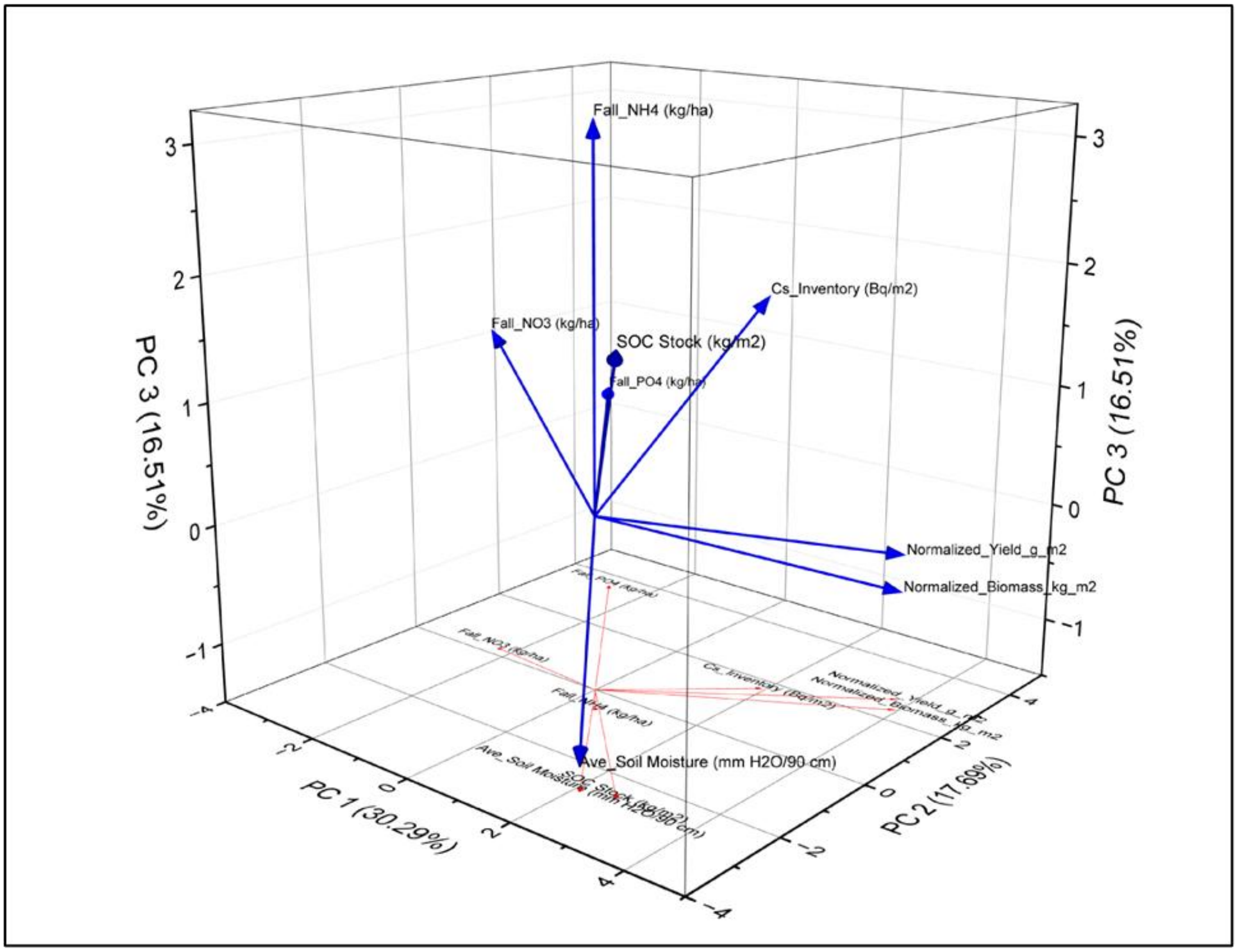

Figure 3. 16. Principal Component Analysis, 2021 – 2023, all sites. Crop response vectors (Normalized Yield and Normalized Biomass) positively correlated with Cs Inventory (a proxy for degree of soil erosion) followed by SOC stocks (a proxy for amount of topsoil present) and soil moisture. Other factors either less correlated, negatively correlated or not correlated with crop responses, indicating the degree of variability and complexity of numerous factors that may influence crop response.

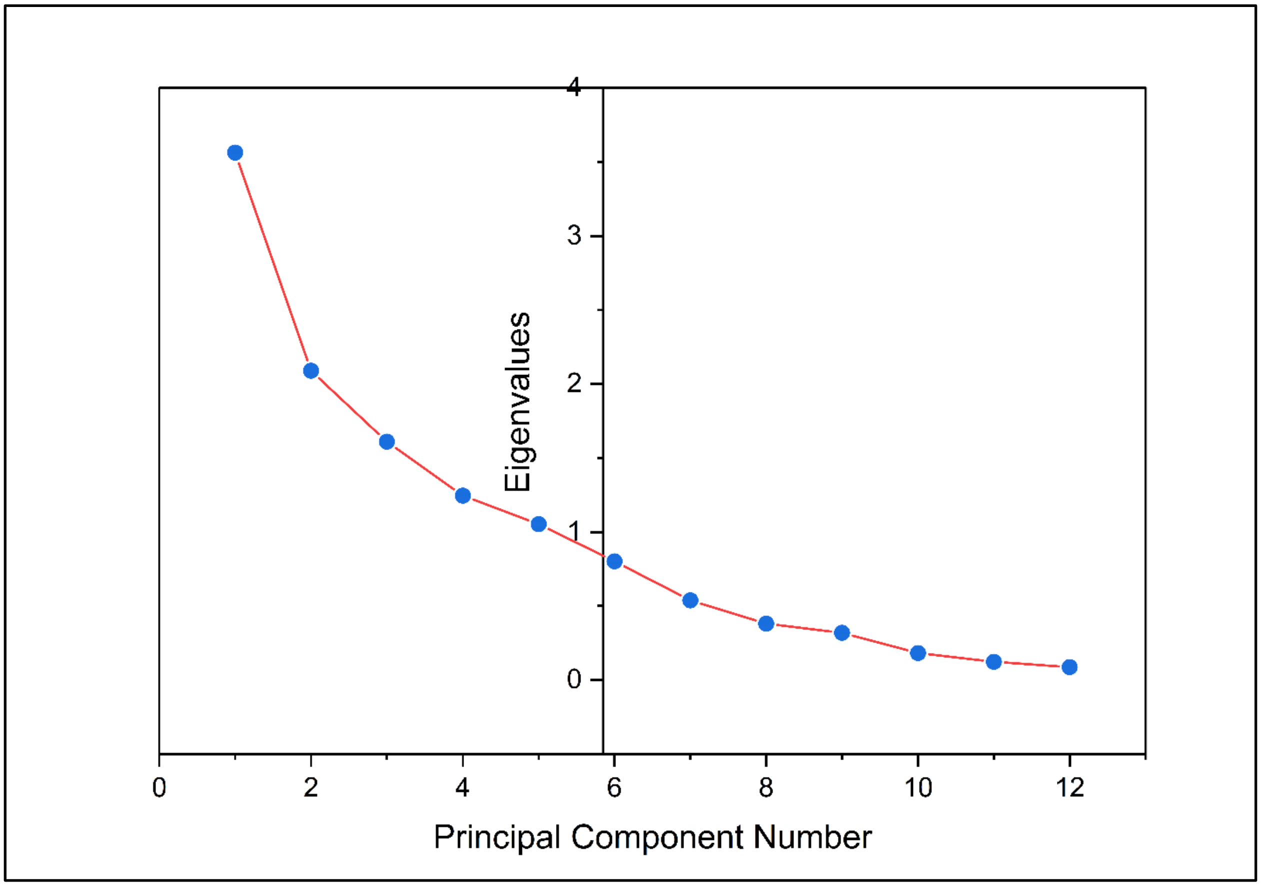

Figure 3. 17. Scree plot of eigenvalues for Principal Component Analysis. This dataset has five principal components with eigenvalues greater than 1.

3.5. Discussion

Variability in both the frequency and magnitude of crop responses to treatments across site-years is assessed to give the most concise interpretation of the results. While some sites tended to be more responsive to treatments than others, only the responsive site-years are assessed for their magnitude of response and compared to similar findings by other researchers. Previous research in southern Manitoba (Smith, 2008) and the northern Great Plains (Schneider et al., 2021) suggest that the greatest response in crop productivity and soil health indicators occurred from soil landscape restoration practices undertaken on the most severely eroded sites, under more favorable weather conditions for growing crops, or both. It was noted that the non-responsive site for yield in South Dakota (Schneider et al., 2023) had a higher rate of erosion (up to 40 Mg ha^{-1} yr^{-1}) than all three sites in Manitoba (15 - 21 Mg ha^{-1} yr^{-1}), though methods of estimation may differ. Like the site in South Dakota, responsive site-years for biomass may only be of secondary interest to producers, but they demonstrate the ability and potential for increased carbon sequestration, with eventual benefits to soil properties and crop yields expected to be realized in the future. In Arkansas, USA, Patton et al. (2024) found cover crops could increase the yield of soybean, but was only observed in one of six site-years. In northwest Mississippi, Prince Czarnecki et al. (2024) found no significant change in SOM accumulation with cover crops and reduced tillage in the first three years in a corn-soybean rotation.

3.5.1. Differences in crop responses among sites

3.5.1.1. Bruxelles

The Bruxelles site was the most responsive site in terms of crop yields to soil landscape restoration as a whole, in that, according to our hypothesis, there are only minor reductions in the removed depression relative to the control depression and significant yield increases in the added knoll relative to the control knoll in three of four years. Only the Bruxelles site achieved crop productivity targets from 2022 – 2024, increasing from 48 – 53% under control conditions to a post-soil landscape restoration ratio of 80 - 94%, with non-significant yield reductions from the removal of topsoil in depressions. Weather data at this site for these three site-years ranged from 90 – 113% of normal for GDD and 59 – 112% of normal for precipitation that produced a positive yield response for three out of four different crops and a single positive biomass response in 2024. An increase in AWHC through the addition of topsoil increased crop yields in the added knoll treatment which met relative yield targets when growing season precipitation was not limiting.

3.5.1.2 Altamont

At Altamont, where an excess moisture limitation in the depression frequently resulted in conditions of standing water, yields in depressions were significantly reduced in three of four years. No appreciable increase in AWHC from added topsoil resulted in a significant yield increase on the knoll in one year out of four. Given this site has the highest clay content and highest SOC content at depth, changes in AWHC due to increases in near-surface SOC from added topsoil were predicted by Minasny and McBratney (2018) to be negligible. Despite this site being assessed as the most eroded of the three sites, challenges at the Altamont site stem from dynamic, hydrologic processes in the landscape, that can reverse the relative moisture status and subsequent crop response between the knoll and adjacent depression, along with the confounding effects of high weed pressure. Topographic features and the presence of subsurface springs, suggest high potential for surface runoff and subsurface transport of water downslope. A positive response to landscape restoration on the knoll was observed one year out of four for canola yield in 2022 and only one year out of four for biomass in 2021. Landscape effects on crop biomass and grain yield between knoll and depression at this site are highly weather-dependent, with wet conditions favouring weed growth at the expense of crop growth, which skews total biomass data and relative crop response data by landscape position to unrealistic and impractical values. Only the Altamont site consistently showed plant populations of wheat and canola below target levels. Rather than assuming seeding rates were insufficient to meet target populations, it is more likely that growing conditions for establishing crops are consistently harsh and extreme in both the depression (due to excess water and high weed pressure) and on the knoll (due to limited water and poor seedbed conditions). As a result, increasing seeding rates to boost low plant populations may be an effective management strategy at Altamont, along with reduced tillage, enhanced crop residue management, inclusion of cover crops and forage crops in the crop rotation, and more aggressive weed management, in addition to soil landscape restoration.

3.5.1.3 Manitou

The Manitou site was assessed as a moderately-eroded, and thus a potentially less-responsive site, in terms of increasing crop productivity through soil landscape restoration. Crop response was non-responsive in all four years, though observations in 2024, with the return to above-normal rainfall, suggested that landscape differences were beginning to decrease, while treatment differences, though non-significant, were beginning to increase. Growing season weather conditions throughout much of the study period were too dry, too often and for too long. The Manitou site produced no significant changes in productivity ratios. Potential increases in AWHC from added topsoil were smaller than for Bruxelles but larger than for Altamont, despite research that increasing SOC should provide the greatest increase in AWHC on loam soils (Masood and Ali, 2023). Continued observations, coupled with crop residue management practices to reduce evaporation and runoff while increasing surface cover, could expose differences in crop responses due to added topsoil, but this is unclear.

Analysis of the subsurface depth of added topsoil resulted in an unusually large increase in the PWP value, limiting the net AWHC increase in the 0-25 cm depth. Soils in the depression (Guerra series) have high water holding capacity with the occasional influence of shallow groundwater tables, whereas the soils on the knoll (Fifere series) have subsoil with limited water holding capacity, especially at depth in the shaly subsoil materials, which were unlikely to be overcome by the modest gains in AWHC from soil landscape restoration. Soil moisture increases in the added knoll treatment were insufficient to produce a significant, positive biomass or yield response over the control knoll. As with the Altamont site, other practices such as crop residue management and cover crops may be required to retain soil water and increase infiltration (Haruna et al., 2020) to make meaningful changes to the AWHC on the knoll at this site.

Olsen P values from these Manitoba sites were considerably higher than those measured by Schneider et al. (2023), particularly at the Manitou site. A history of manure application prior to the 1990s may explain some of these elevated soil test P values at this site.

3.5.2 Soil moisture management

Four soil moisture measurements during the growing season may not be adequate for a complete account of the fate of soil moisture for a growing crop. Rarely was soil moisture measured immediately after a major precipitation event, as field trafficability would be limited Given that soil moisture content should be at or above field capacity at that time, it may be helpful to have more data after precipitation events to measure infiltration into the profile or runoff on eroded hilltops. Poorer crop stands on the control knolls could have increased evaporation due to low canopy cover but could also have reduced plant water uptake due to fewer plants and poorer growing conditions. By contrast, knolls with added topsoil may conserve moisture due to increased canopy cover, but could also use more water from improved plant stands and have more early-season evaporation due to the darker colour of the added topsoil. Similar to these findings, in Ohio, USA, increasing available water was determined to be the key factor influencing corn yields, bulk density, K_{sat}, and water-stable aggregates (Tenywa et al., 2001). Other examples were observed by Smith (2008) in Manitoba, in which some added topsoil samples did not increase AWHC. In Australia, He and Wang (2019) found a critical AWHC value (i.e., a stored soil moisture value), closely correlated with rainfall outside the growing season, above which wheat yields do not increase further.

3.5.3 Fall nutrient carry-over

Similar to the increased weed pressure at Altamont, differences in crop responses on the knoll positions may have been masked in some instances by agronomic factors such as surplus macronutrients on the knolls, regardless of topsoil additions. It may be the result of repeated, blanket fertilizer applications based on the average or representative soil test results that do not account for extreme locations in the landscape. Lack of crop productivity on the knolls, in particular, could result in minimal nutrient uptake and subsequent carry-over, especially during years of low precipitation. Smith (2008) saw significant increases in nitrate-N, Olsen P, SOC and EC in the 0-15 cm depth at the Treherne, Manitoba, site when topsoil was added and compared to the control plots. Addition of topsoil, when soil moisture and temperature conditions are suitable, may also encourage mineralization of N and P, but this was not measured to confirm. Combining ammonium-N and nitrate-N to compare plant-available nitrogen (PAN) values to Schneider et al. (2023) resulted in similar residual values in both control and rehabilitated plots, but Olsen P values from the Manitoba sites were considerably higher than those measured by Schneider et al. (2023), particularly at the Manitou site. A history of manure application prior to the 1990s at this site may explain some of these elevated soil test P values. Values from PRS® probes indicated high nutrient supply values of N and P on the knolls at Altamont, Bruxelles and Manitou sites. These values may reflect low crop nutrient uptake, either due to drought conditions, low plant populations or a history of excess fertilizer applications (Dr. Eric Bremer, Western Ag Innovations, personal communication; https://www.westernag.ca/innovations/customer/interpretation).

3.6. Conclusions

Crop yield and biomass increase due to soil landscape restoration were site-specific and year-specific. Factors influencing the crop response to soil landscape restoration included: severity of erosion, extremes in water-holding capacity of soils (both lack of available water on knolls and excess water in depressions) and management factors such as crop establishment practices at seeding, fertilizer application and weed control. Temporal variation of weather factors (precipitation and, to a lesser extent, growing degree days) among growing seasons may have reduced crop response to soil landscape restoration due to drier-than-normal precipitation levels in 2021, 2023 and the latter part of the 2024 growing season.

Crops grown at the Bruxelles site responded positively to added topsoil, significantly increasing yields in three years out of four. Crop yields at the Altamont site were much less-responsive to added topsoil, only increasing significantly in one year out of four; and at the Manitou site, crop yields were consistently unresponsive.

Total and available soil water increased somewhat with landscape restoration, but the frequency and magnitude of these increases, if any, depended on site, amount and timing of growing season precipitation and crop water utilization. Increases in nutrients (N and P) from added topsoil were the result of a combination of nutrients transferred upslope with topsoil during soil landscape restoration activities (one-time) and previous buildup of unused nutrients following multiple growing seasons of limited soil moisture (repeated over many years). Olsen P and, to a lesser degree, nitrate-nitrogen, were retained on knolls due to lack of sufficient moisture to promote substantial leaching or runoff, as well as exposed subsoil with elevated carbonates, in some instances. Other biological and management factors, such as lower plant populations and higher weed populations, were more likely to mask differences in crop performance rather than accentuate them.

Overall, re-distributing topsoil within a variable landscape to change various soil properties (as shown in Chapter 2) was relatively straightforward to accomplish; however, demonstrating that these changes produced significant, positive and consistent crop responses (yield and biomass) was much more difficult to achieve during the study period. The relocation of topsoil did result in negative crop responses in depressions where topsoil was removed, in four of 12 site-years, which is a risk in conducting this practice, but these responses, like the positive responses to added topsoil, were site- and weather-dependent.

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Chapter 4

Crop response to topsoil redistribution under controlled growing conditions

4.1. Abstract

The addition of topsoil to eroded knolls as a means to improve crop productivity (aka landscape restoration or soil-landscape rehabilitation) is a promising endeavor, but it is difficult to replicate and randomize field experiments with field-scale equipment, let alone to include multiple treatments such as multiple topsoil depths.

Soil cores, 20 cm in diameter, were collected from two landscape positions (knoll and depression) at three sites in south-central Manitoba. Topsoil depths of 0, 10, 20 and 30 cm were cut and removed from depression cores and added to the tops of knoll cores to simulate the practice of landscape restoration as a means to counteract the negative effects of tillage erosion. New soil columns were constructed to be 60 cm long through cumulative depths of added or removed topsoil, remaining or existing subsoil and a base of inert, medium-grade, granular silica sand.

Soil columns were placed under controlled conditions of light, temperature, fertility and water applications for two growing season "phases" of wheat, followed by a third phase using flax. In spring of 2024, the columns were moved outdoors under natural light and rainfed conditions to conduct a fourth growing season experimental phase with barley. At the end of each crop phase, crops were harvested and measured for total biomass and grain yield.

Statistical analyses of these parameters, along with repeated measures analysis of volumetric soil moistures from 10 to 40 cm depth, were conducted and analyzed for significant differences of means by site, landscape position, treatment and any interactions. While not every treatment comparison could be distinguished as significant from the others, key differences appeared often enough to interpret the most effective depths of topsoil removal and addition for designing a soil-landscape restoration plan. Overall, removing 10 cm of topsoil (from up to twice the land area for

topsoil source as the target application area) and adding 10 - 20 cm of topsoil provided the most consistent and effective depths of topsoil to remove and apply in a landscape restoration strategy.

4.2. Introduction

The addition of topsoil to eroded knolls as a means to improve crop productivity (aka landscape restoration or soil-landscape rehabilitation) is a promising endeavor, but field variability and limited time to prepare and test in the "shoulder seasons" (i.e., early spring, prior to planting and late fall, after harvest) reduce the ability to fine-tune recommendations such as how much topsoil to add to eroded knolls. It is difficult to replicate and randomize with field-scale equipment, let alone to include multiple treatments such as multiple topsoil depths. Field experiments often used one depth of topsoil removed and added, and compared to control plots were no topsoil was re-distributed. Previous research examined the effect of added topsoil from as little as 5 cm (Verity and Anderson, 1990; Larney et al., 2009) to 15-20 cm (Schneider et al., 2021; Smith, 2008).

As a means to more precisely explain the effect of a particular factor on crop growth and productivity, "pot studies" grown under controlled conditions, such as a greenhouse, growth chamber, or similar facility, can be employed. Pot experiments have a greater ability to detect responses under controlled conditions than field plots (De Vries, 1980), but these responses may not be meaningful when tested under field conditions, or may produce inconsistent results due to several random factors from multiple site-years (Montesinos, 2024). In general, when compared to field experiments, pot experiments are less likely to produce type I statistical errors (false positives) but more likely to produce type II statistical errors (false negatives) because factors studied in the field may be ignored in pot experiments. Wu et al. (2011) compared 10-L pots of packed soil to a bulk density of 1.35 g cm^{-3} to field plots for differences in transpiration shoot dry weight for maize and winter wheat in China. They found field plots were more effective than pots for dry shoot weight and total transpiration under similar soil water treatments, but the overall trends were not significantly different.

Pot studies have been conducted for numerous agricultural purposes, including, but not limited to: salinity experiments (Tavakkoli et al., 2012); fertilizer studies, to compare fertilizer placement methods (Ferron et al., 2024), the uptake of certain constituents in plants, such as cadmium (Jiao et al., 2004) or labeled nutrients such as ^{15}N to serve as a tracer (Tomar and Soper, 1987). Comparison of watering regimes were conducted by Ray and Sinclair (1998) and Poorter et al. (2012a). Other pot experiments relating to soil factors include: long-term (20 year) organic matter decomposition (Wadman and de Haan, 1997); evaluation of soil conditioners (Dalling et al., 2013) and super absorbent polymers, (Zheng et al., 2023).

Previous pot studies specifically conducted to examine the effects of soil erosion include Gao et al. (2015), where topsoil loss was simulated by mixing reduced depths of topsoil with subsoil to a tillage depth of 20 cm. They produced, on average, a 6% crop yield loss for every 10 cm of soil loss from 0-70 cm. Zhang et al. (2024) conducted an outdoor pot experiment in China using pots 37 cm long, 27 cm wide and 34 cm tall planted to smooth brome grass to compare soil erodibility with current soil erosion status (none to severe). In Germany, Pehlivan et al. (2025) used 10.5 cm diameter x 35 cm height pots to plant rapeseed (*Brassica napus,* L.) into a Luvisol with various degrees of topsoil dilution mixed with subsoil.

Considerations when designing a pot study are adequate pot size (Poorter et al., 2012b; Ray and Sinclair, 1998) and adequate porosity for drainage (Passioura, 2006). Sizes of soil cores vary in shape, diameter and length with almost every experiment, likely a function of available sampling equipment and containers. Pot diameters from select experiments ranged from 4.45 cm (Bricklemeyer et al., 2011) to 56 cm (Wacha et al., 2021), with heights ranging from 7.5 cm (Ding et al., 2024) to 90 cm (Hohmann et al., 2016). In Manitoba, Erb (2005) and Wang (2007) collected intact soil cores from a site north of Brandon, MB with dimensions 20-cm diameter and 30-cm long for measurement of greenhouse gas flux. Given no general consensus on standardized pot diameters and lengths, it is inferred that all pot sizes are acceptable, provided scientific principles are followed and it is recognized they all possess limitations in their representation of actual field conditions.

Choosing to use intact cores versus loose soil materials re-packed to resemble in-situ bulk density (sieved to less than 2 mm, packed in uniform layers) has a major benefit, in that they mimic actual in-situ conditions, but the downside is the time-consuming, labor-intensive, sampling that may lead to soil compaction in the cores, as discussed by Ikoyi and Schmalenberger (2021). Re-packed soil columns may overcome sampling challenges of intact soil cores, but may produce unrealistic bulk densities, preferential flow paths or lack of hydraulic connectivity between soil layers. Hohmann et al. (2016) conducted a pot experiment using 120-L trash bins filled 90 cm deep with imported topsoil and subsoil for detailed phenotyping of winter oilseed rape (*Brassica napus* L.) populations under semi-controlled growth conditions (foil house). They extrapolated crop growth from soil-grown container plants to make field-scale yield predictions under optimal and stress conditions. Tavakkoli et al. (2012), in their salinity trial in Australia, used 10.4-cm diameter, 32-cm deep pots with two layers of soil packed to bulk density of 1.35 g cm^{-3}, plus plastic beads between topsoil and subsoil layers to prevent capillary action into topsoil and on the soil surface to minimize evaporation on the surface. This experiment proved to be an effective screening procedure for evaluating barley varieties on a moderately saline field site.

Artificial light conditions represent a potential pitfall of controlled-environment pot studies as discussed by Poorter et al. (2012a). Along with a number of artificial growing conditions, including reductions in nutrient availability, AWHC of soil, limited root growth in pots and changes in soil temperature, artificial light intensity often results in suppressed development of plants grown in pots. This highlights the need for adequate artificial lighting, luxuriant nutrient supply (if testing factors other than nutrients), moderate temperatures and adequate pot size to ensure the pot studies are reasonably mimicking field conditions.

Concerns with bypass flow (i.e. either *macropore flow*, from large cracks within soil cores or *sidewall flow*, from gaps between the soil core and the column wall) when using intact cores from no-till (NT) management were described by Miranda-Vélez et al. (2023), using 20-cm x 20-cm intact soil cores. Leaching of solutes commences and peaks earlier under NT than conventional tillage (CT), but total leached nitrate was greater under CT due to the bypass effect. Of greater concern is the issue of sidewall flow between soil cores and the container walls. Corwin (2000), using soil lysimeters with disturbed soil cores (60-cm diameter and 1.83-m height), proposed using annular rings to divert sidewall flow near the soil surface (7.5 cm) into the soil column, but this proved to be a tedious process, and, while significantly reducing sidewall flow to undetectable levels, may have altered water flow patterns in the soil cores. Derby and Knighton (2002) used 61-cm diameter and 1.68-m deep soil cores in North Dakota, USA, which functioned adequately for 6 years of operation, but possible sidewall flow was observed. Injecting expanding polyurethane foam to fill voids between the poly-vinyl chloride (PVC) wall and soil core was suggested to curb sidewall flow, as was done by Strock and Cassel (2001). Given all the limitations pertaining to pot experiments, it is important to identify specific treatments in the field and design experiments that focus on those treatments with minimal confounding factors in the experimental design (Montesinos, 2024).

As described in previous chapters, field-scale experimental plots were established in undulating to hummocky landscapes with evidence of tillage erosion, by which topsoil was removed from depressions and placed at a single depth on eroded knolls to examine differences in crop performance from untreated plots under field growing conditions. Although differences between control (untreated) and restored treatments vary by site and growing season, there are several random factors that may mask differences in soil properties and crop performance over site-years. Also, limited resources and space at each field site only permitted the comparison of one depth of removed and added topsoil to a control with no topsoil re-distribution. As a complement to the large-plot field experiments in previous chapters, a series of controlled experiments were conducted in 2023 and 2024 using soil collected from the field and placed into columns, carried out under controlled conditions of lighting, temperature, added nutrients and moisture, while other landscape/topographic features such as elevation, slope, slope curvature, and depth to water table were removed. The objective of this study was to determine the depth of topsoil to be added to an eroded knoll until positive differences in crop performance are observed, and the depth of topsoil removed from a depression before there are negative changes in crop performance.

It is anticipated that there would be additional statistical power, when compared to field experiments, to assess significant differences among specific treatments, especially between different depths of added topsoil as compared to control (untreated) cores from the knoll and depression. It is entirely possible that to achieve the best overall agronomic result, the depth of soil removed may not necessarily be the same as the depth of soil applied.

4.3. Materials and methods

4.3.1. Sample collection

A total of 96 intact soil cores from two landscape positions (16 from the knolls and 16 from the depressions) from each of the three field sites where landscape restoration trials were underway at Altamont, Bruxelles and Manitou, MB were collected in the fall of 2021. The field studies were essentially a comparison of untreated plots within an eroded knoll and an adjacent depression with restored plots in which 20 cm of topsoil (15 cm at Altamont) was removed from the depression and placed on the knoll. In terms of treatments used in the column study, the field studies also used the treatments, when cross-referenced, include "control depression" (D_0), "removed depression" (D_{20}), "control knoll" (K_0) and "added knoll" (K_{20}).

Samples were collected within 5 – 10 meters adjacent to, but outside of, the field study areas at each site. A hydraulic truck-mounted probe was used to extract 30-cm long cores from the knolls and 40-cm long cores from the depressions using 20-cm inner-diameter poly-vinyl chloride (PVC) pipe of 6.4-mm wall thickness, similar to those used by Wang (2007) and Erb (2005), with bottom edges beveled and a 25-cm diameter, 12.7-mm thick metal plate placed on top of the PVC column to push into the soil. Once pushed to the desired depth, the soil columns were extracted using a hand shovel and each placed into a 20-L plastic pail for transport. The columns were stored indoors at room temperature until the time of construction.

4.3.2. Column construction

Soil columns were prepared using the following method: an angle grinder and reciprocating saw were used to cut through the PVC column and remove the surface 10, 20, or 30 cm of topsoil (intact) from depression cores. A horizontal hydraulic jack and metal disk, 19.2-cm diameter and 12-mm thick, was set up to push the original soil core out the bottom of its 30- or 40-cm long pipe and into the top of a new 65-cm long pipe to the desired depth, using a rubber collar with hose clamps to connect the two pipes for a smooth transition from one pipe to another. An adjustable metal spacer, consisting of two metal plates each 6 mm thick, with an internal diameter of 19 cm and adjustable bolts, was used to hold the original soil column in place, leaving room for the depth of added topsoil, while the column was inverted to add the desired depth of silica sand (Granusil® mineral filler, crystalline silica in the form of quartz, CAS # 14808-60-7, "medium grain size")

The bottom of the column was covered with cloth and a plastic disk (made from 3- mm thick high-density polyethylene plastic sheets, 19.2-cm diameter) with ten holes, each 2 mm in diameter, for excess water to drain out. Once the bottom was held in place with screws and sealed with silicone, the columns were placed right-side-up, the spacer was removed and the topsoil cut from the donor column was placed on top of the new column and pushed into place. Four "blank" soil columns of 60-cm height of pure silica sand were included for a total of 100 soil columns. The sand was to serve as an inert material to bring all soil columns to the same overall column length, while reflecting the differences in solum length by treatment. Bulk density of the sand layer was approximately 1.6 g cm^{-3}, slightly greater than the bulk density of subsurface layers found in the field. Surface layers were added with as little disturbance as possible and were not inverted upon insertion. No tillage of the soil in the columns reflected a no-till environment that was implemented at two of the three field sites. All columns had a target freeboard (i.e. from the soil surface to the top of the soil column) depth of 5 cm to allow water to pond during watering applications.

A total of 100 soil columns (3 sites × 8 treatments × 4 replicates, plus four control columns of pure sand), each with an approximate material volume of 18.8 L, were used in this study, according to the treatment design in Figure 1, and described as follows:

Treatment 1 (K_0): knoll cores with no topsoil added (control);

Treatment 2 (K_{10}): knoll cores with 10 cm of topsoil added;

Treatment 3 (K_{20}): knoll cores with 20 cm of topsoil added;

Treatment 4 (K_{30}): knoll cores with 30 cm of topsoil added;

Treatment 5 (D_0): depression cores with no topsoil removed (control);

Treatment 6 (D_{10}): depression cores with 10 cm of topsoil removed (added to K_{10});

Treatment 7 (D_{20}): depression cores with 20 cm of topsoil removed (added to K_{20});

Treatment 8 (D_{30}): depression cores with 30 cm of topsoil removed (added to K_{30});

Treatment 9 (B_{60}): "blank" columns of 60 cm of only silica sand.

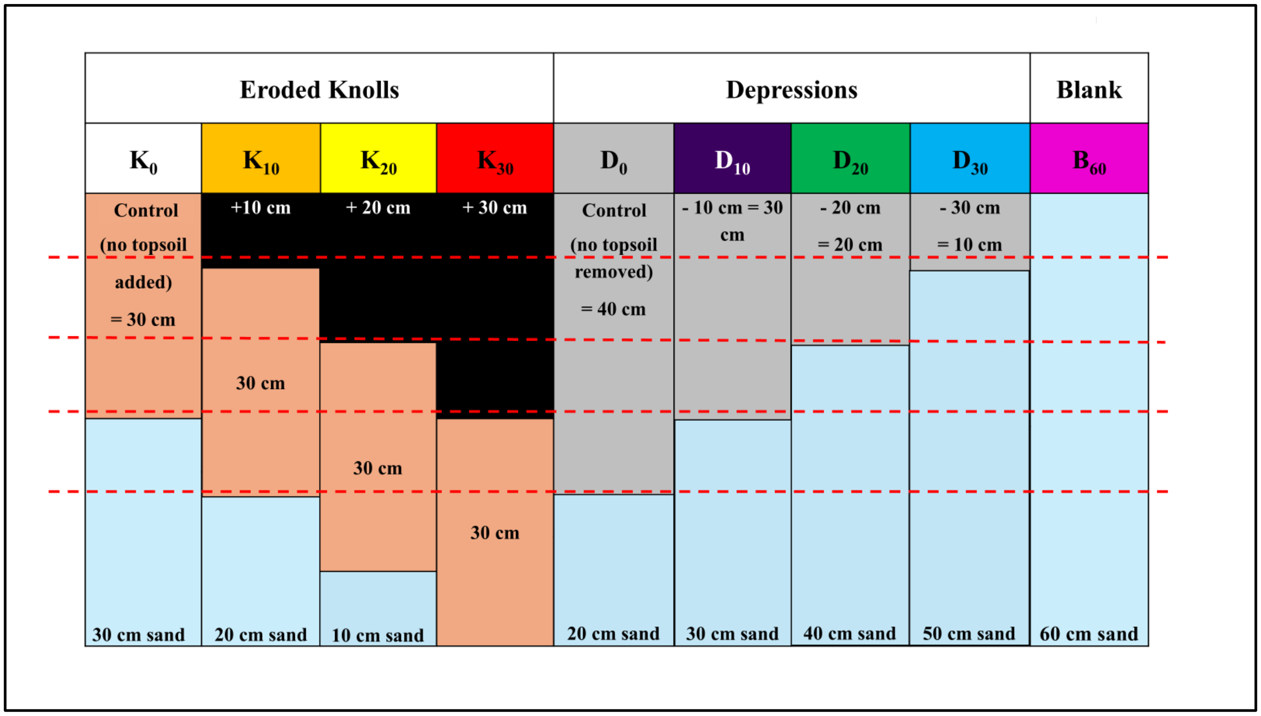

Figure 4. 1. Soil column treatment design. Topsoil transfers occur from D_{10} to K_{10}; from D_{20} to K_{20}; and from D_{30} to K_{30}. Red dashed lines represent approximate depths of soil moisture measurements (10, 20, 30 and 40 cm) and the type of soil material found at these depths. Orange represents the original soil from the hilltops; grey represents the original soil from the depressions; black is the depth of topsoil removed from the depressions and added to the hilltops; and blue is the depth of sand added to the base of the soil columns to bring the overall column length to 60 cm.

4.3.3. Experimental design

The placement of the columns was randomized on four wooden pallets, 1.2 m long and 1.2 m wide, in four replicates. Four separate runs of crops were grown in these columns to maturity and harvested for grain yield and aboveground biomass. Phase 1 was planted to spring wheat (*Triticum aestivum,* L.) and grown from Mar 6 - June 12, 2023. Phase 2 was also planted to spring wheat from Sept 5 – Dec 6, 2023, with additional lights, guards and reflective walls to enhance plant growing conditions, with Plant Root Simulator (PRS®) probes, ion exchange resin membranes in plastic supports, installed in the topsoil to measure nutrient supply and availability (Western Ag

Innovations, Saskatoon, SK; www.westernag.ca/). Phase 3 was planted to flax (*Linum usitatissimum,* L.) and grown from Jan 10 – May 3, 2024, with the same setup as Phase 2 but without PRS probes. Phase 4 was planted to barley (*Hordeum vulgare,* L.), grown from May 10 – Sept 11, 2024, and conducted outdoors until Aug 22 using 6 fewer columns, as one K_0 column and one D_0 column from each site were destructively-sampled for moisture retention determinations prior to initiation of this run. Pots remained on their respective pallet throughout the entire study. No watering of the columns was conducted between phases of the study.

For phases 2 to 4, guard columns were placed around the perimeter of the replicates using the leftover 40-cm long PVC pipe filled with potting soil and placed on elevated shelving to match the height of the treatment columns. Soil moisture probe access tubes (25-mm diameter, 56-cm long) were installed vertically with a 32-mm diameter, 46-cm long drill bit to a depth of 40 cm in one replicate of soil columns (25) to measure volumetric soil moisture at depths of 10, 20, 30 and 40 cm bi-weekly during the growing period with a Delta-T®, SDI-12, PR2 profile probe connected to an HH2 Moisture Meter (Delta-T Devices, Cambridge, England). Actual moisture depth measurements were approximately 6 cm above each of the four target depths (i.e., 4, 14, 24 and 34 cm) due to average length of 6 cm of moisture tube exposed above the soil surface, thus avoiding moisture measurements occurring exactly at the interface of different soil layers. Plant root simulator (PRS®) probes were installed vertically in two separate replicates during phase 2 in wheat for approximately 1 week (Sept 18 - 25) to measure nutrient supply.

Four phases of crops were planted to measure the growth response (biomass and yield) to topsoil depth, with soil fertility optimized to minimize nutrient deficiencies, while maintaining light intensity and temperature as uniformly as possible. Watering of the columns was based on soil moisture and crop health status of the D_0 columns and was applied using a target water volume, a garden hose of known flow rate, timed with an online metronome application through a cell phone, to ensure consistent amount of water added for each column. Depending on the water needs of the crop, volumes of water added at specific watering events were either 0.25 L (8.0 mm), 0.315 L (10 mm) or 0.5 L (15.9 mm). Metronome settings were 56 beats per minute (BPM) for 0.25 L and 26 BPM for 0.5 L, respectively.

The watering strategy applied to Phases 2 – 4 was to ensure adequate moisture for crop establishment, followed by limited periods of moisture stress without leading to crop death but to accentuate any differences among treatments and sites in water holding capacity. The decision to water all columns with the same volume of water was based on soil moisture measurements of D_0 columns, as well as early warnings of reduced plant vigor and drought stress from the shorter guard columns, where the potting soil had considerably less water holding capacity than any of the treatment columns. Water-soluble fertilizers (21-7-7 and 10-52-0) were surface-applied at agronomic rates to supply 168 kg N ha^{-1} and 45 kg P_2O_5 ha^{-1} immediately after planting with the initial watering to simulate fertilizer application in the field.

LED greenhouse lights (Sungrow™ Quantum) were placed 86 cm above the top of the columns and operated on a timer at the 100% brightness setting for 16 hours per day. Four lights (one per replicate) were used during Phase 1, but was increased to eight (two per replicate) during Phases 2 and 3 to increase light intensity. Light intensity was 185-344 µE m^{-2} s^{-1} during Phase 1 and 226-471 µE m^{-2} s^{-1} during Phases 2 and 3 as measured using a Quantum Flux meter (Model MQ-500, Apogee Instruments®, measured in µmol m^{-2} s^{-1}) by holding the sensor over the top of each column and recording the value

Ambient temperature of the room (along with minimum and maximum values per 24-hour period) was recorded daily during each growing period. Soil temperature at 5 cm depth was recorded twice per week in three of the D_0 columns (one for each site) and a B_{60} column in the same replicate used for soil moisture measurements.

After harvest of Phase 3 was completed (May 3, 2024), destructive sampling of six select soil columns (K_0 and D_0 for each site at 10, 20, 30 and 40 cm depths) was conducted to determine available water holding capacity (the difference in volumetric moisture content from field capacity (pF 1.8) and wilting point (pF 4.2)), bulk density, porosity and particle size. These samples were collected using 8 cm diameter, 5 cm height Hyprop rings and analyzed to generate a moisture retention curve fit with traditional constrained van Genuchten-Mualem modeling using the Hyprop apparatus (Meter Group, Inc.). To confirm soil textures of the soil layers by depth and by site, particle size was determined using a laser diffraction unit (Dr. Alex Koiter, Brandon University – Table C2).

To determine the extent of crop growth limitations using indoor lighting and precipitation, Phase 4 of the experiment was conducted outdoors with the remaining soil columns from May 10 to Aug 22, 2024, using barley as the test crop. Natural sunlight (up to 1500 $\mu E\ m^{-2}\ s^{-1}$) and precipitation events replaced greenhouse lights and watering. The columns were surrounded by wire fence to prevent predation by deer. The columns were brought indoors prior to harvest.

Target populations of wheat (cv AAC Brandon, planted at 10 seeds per column, approximately 2.5 cm deep), flax (cv Rowland, planted at 30 seeds per column, approximately 1.25 cm deep) and barley (cv Ezma, planted at 10 seeds per column, approximately 2.5 cm deep) were planted and thinned to 8, 23 and 8 seeds per column, respectively, 7-10 days after emergence. A cereal seeding template consisted of 3 mm thick plastic disk with 10 holes, each 9 mm in diameter. Weeds were removed by hand as they appeared. Plant height was measured immediately prior to harvest. Grain yield and total biomass were taken at harvest by cutting the plants 1-2 cm above the soil surface, weighing the sample and harvesting using a table-top, stationary harvester (Simpler Sampler® Portable Combine by Dimo's Labtronics, Winnipeg, MB Canada). Wheat and barley grain yield was recorded and dried at 60ºC for 24 hours to determine grain moisture content and corrected to a standardized moisture content for each crop (14.5% for wheat; 10.0% for flax; and 14.8% for barley). The small sample size for flax did not permit drying; instead grain moisture content was assumed to be uniform across samples at 10.0% moisture content. Normalized grain yields were calculated separately for each crop by dividing the individual sample yield by the maximum yield in each crop phase.

K_0 represents the control (untreated) knoll columns which serve as the lower reference point in terms of soil properties and crop productivity. These columns are from the least productive part of the landscape where attempts to improve productivity were conducted with the addition of topsoil from depressions. By contrast, D_0 represents the control (untreated) depression columns and serve as the upper reference point in terms of crop biomass and crop yield, to which improvements to the knoll columns were compared as a measure of success in changing soil properties and crop productivity. B_{60} are "blank" columns that demonstrate the inert nature of silica sand acted as a medium for growing plants due to its negligible water holding capacity and fertility. Biomass and crop yield produced in these columns were negligible.

4.3.4 Statistical analyses

The columns were set up as a Randomized Complete Block Design with four replicates of 25 columns, each treatment from each site (soil type) present in every replicate. Primary response variables were grain yield and total biomass, with the following fixed effects: phase (crop type), landscape position (with a dummy variable factor of check (0), topsoil added (1), or topsoil removed (2) nested within position), treatment (topsoil depth) (with factor (topsoil added, removed or check) nested within position), site (texture) and the various interactions (treatment × position, site × treatment, site × position and site × treatment × position). Replicate (block) was considered a random effect. Repeated measures analysis of soil moisture values of Phases 2 - 4 serve as supporting data to determine the impact of topsoil depth and soil type on crop response. Linear mixed models using SAS® (SAS Online for Academics, SAS Institute, 2024) were used in the ANOVA, with an $\alpha = 0.05$ to determine significant differences in fixed and random effects. Means comparisons were conducted using the Tukey-Kramer method. The SAS Glimmix model is a generalized linear mixed model-based analysis that uses ANOVA and accommodates non-normal data that may also have unequal variances (Stroup, 2015). *A priori* contrasts were conducted among specific treatments to confirm any significant differences in crop yields. Graphical depictions of selected data were constructed using R® software (version 4.4.1, R Core Team, 2024).

4.4. Results

Analyses of all phases of the crop data (yield and biomass) produced several interactions, making it difficult to compare all aspects of the model. Due to changes made in the growing conditions in between runs of different crops, and for greater ease of interpretation, the crop phases were examined independently.

4.4.1. Growth factors

Crops such as spring wheat, barley, oats, canola and flax require a minimum accumulation of about 1,200 Growing Degree Days (GDD) above 5°C to reach maturity (Government of Manitoba, 2022; Agriculture Canada, 1977). Daily minimum and maximum ambient soil temperatures were used to calculate Growing Degree Days for Phases 1 – 3 (Table 4.1). Soil temperatures at 5-cm depths in D_0 columns and one B_{60} column did not vary from one another by more than 2°C per measurement event (not reported). Soil temperatures ranged from 18 – 26°C across measurement events from Phases 2 and 3. Data from Table 4.1 (indoor) and Table 4.2 (outdoor) indicates that GDD requirements were met in all four phases. Phase 1 (wheat) had the lowest light intensity of all phases, but this was remedied by doubling the amount of greenhouse lights from four to eight for Phases 2 and 3.

Table 4. 1. Growing conditions for the four phases of the column experiment.

Phase	Crop	Added Water (mm)	Growing Degree Days	Light Intensity Range (μmol m^{-2} s^{-1})	Lights On/Off
1	Wheat	226	1640	185 - 344	7 am – 7 pm
2	Wheat	213	1543	226 - 461	5 am – 9 pm
3	Flax	157	1757	262 - 471	5 am – 9 pm
4	Barley (outdoors)	340	1479	340 - 2250	Natural sunlight (approx. 6 am - 9 pm)

Table 4. 2. Weather summary data for Portage la Prairie, MB, 2024 growing season.

Month	% of Normal Precipitation	% of Normal Growing Degree Days
May	262	102
June	145	99
July	76	107
August	84	101

Although light intensity was increased, it was still at the lower end of the range experienced under natural sunlight from May to August, 2024 in Phase 4. Phase 3 (flax) received the least amount of applied water, but was sufficient to bring the flax crop to maturity in all treatments. Phase 4 (barley) was conducted outdoors and had the lowest number of GDD of all the runs but was still sufficient for crop growth. Precipitation during this phase was in excess during May and June, but became limited in July and August.

Yields from column experiments did not accurately reflect yield expectations from field conditions, as there are a number of limitations to crop growth in controlled experiments such as lack of light intensity and limited soil volume for root growth. However, relative differences in normalized yields and biomass still provide meaningful insights as to anticipated crop responses from treatments when imposed under field conditions.

4.4.2. Crop performance assessments

4.4.2.1. Landscape differences (K_0 < D_0):

No significant differences in biomass between K_0 and D_0 were observed in any of the crop phases, although D_0 had numerically greater biomass than K_0 in the barley phase (Figure 4.2; Table 4.3). ANOVA for crop yields (Table 4.4) revealed several significant effects for various factors and interactions, but they did not always result in significant differences among specific treatment comparisons. Contrasts between K_0 and D_0 revealed significant differences in the wheat ($P < 0.0001$) and barley ($P = 0.0091$) phases, but not in the flax phase ($P = 0.8040$) (Table 4.5). Of the 12 comparisons of normalized yields of K_0 versus D_0 by site and crop phase (Tables 4.6), K_0 is numerically lower-yielding than D_0 in 11 of the comparisons (except at Bruxelles under flax), even when landscape features are removed and growing conditions are uniformly applied.

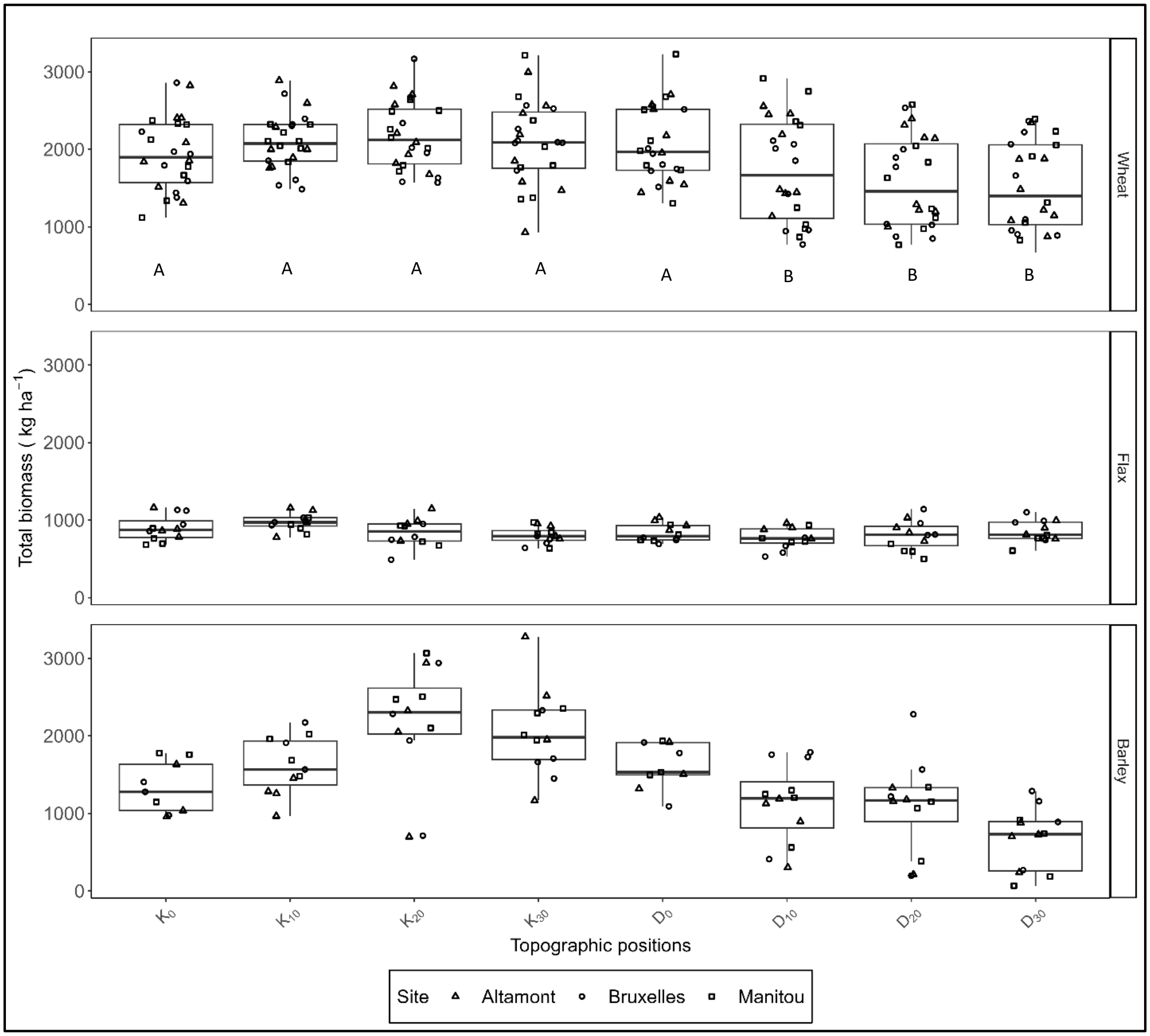

Figure 4. 2. Boxplot distributions of total biomass by crop phase. Wheat biomass ANOVA at α = 0.05 had a significant position effect with $P = < 0.0001$; flax biomass ANOVA at α = 0.05 had a significant site × treatment × position interaction with $P = 0.0008$; and barley biomass ANOVA at α = 0.05 did not have any significant effects. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05.

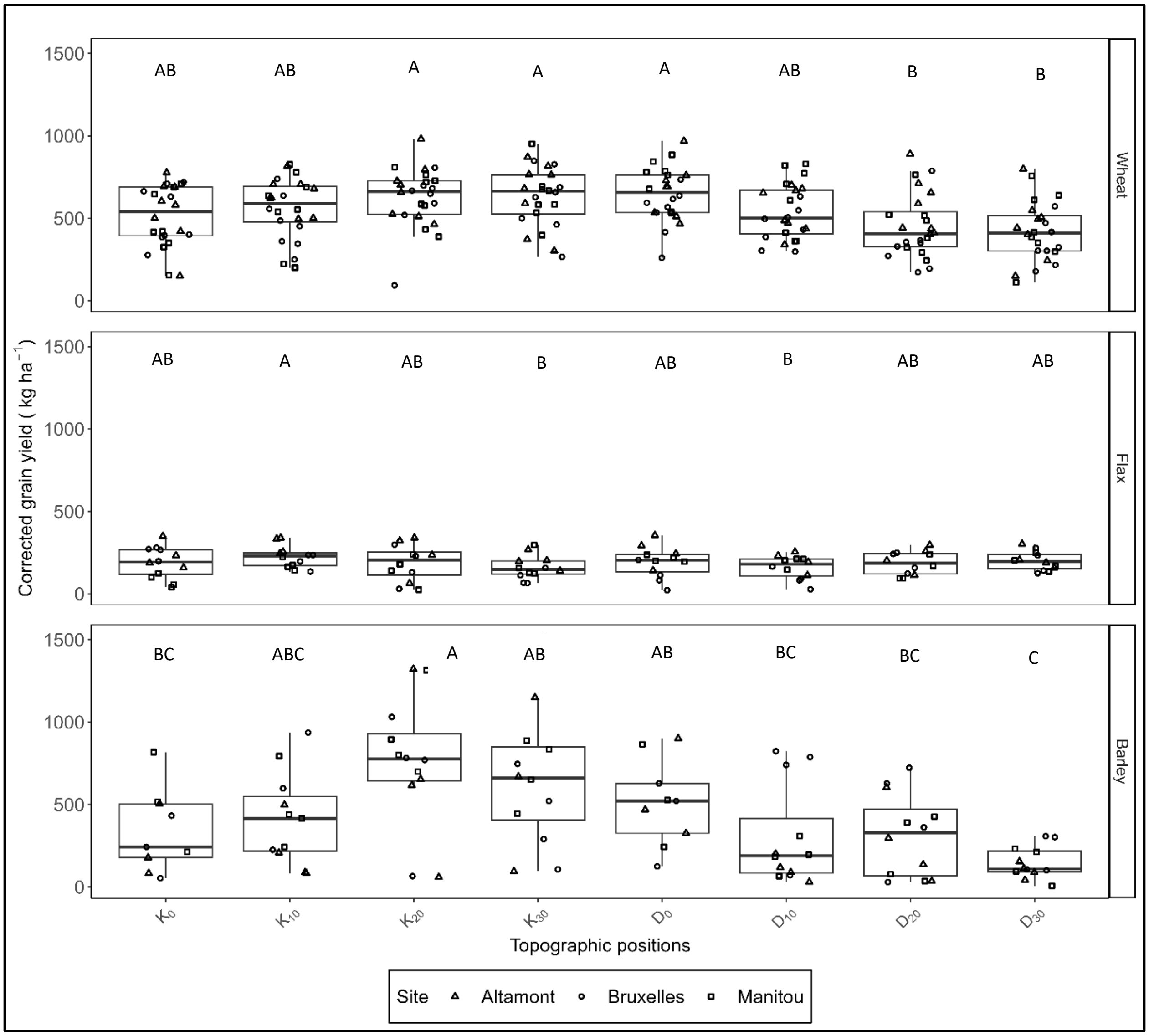

Figure 4. 3. Boxplot distributions of crop yields by phase. Wheat yields ANOVA at α = 0.05 had a significant treatment × position interaction with $P = 0.0187$; flax yields ANOVA at α = 0.05 had a significant treatment × position interaction with $P = 0.0065$; and barley yields ANOVA at α = 0.05 had a significant treatment × position interaction with $P = 0.0212$ and a site × position interaction with $P = 0.0297$. Boxplots superseded by different letters are significantly different based on Tukey Kramer means separation at α = 0.05.

Table 4. 3. ANOVA table for total biomass.

Crop (Phase)	Wheat (1 and 2)	Flax (3)	Barley (4)
Effect		Biomass (kg ha^{-1})	
ANOVA		*P* value	
Treatment	0.6759	0.2148	0.3257
Position	**<.0001**	**0.0141**	0.0587
Treatment × Position	0.6412	**0.0003**	0.2251
Site	0.6843	**<.0001**	0.4911
Site × Treatment	0.7670	0.1235	0.5367
Site × Position	0.7976	**0.0268**	0.2963
Site × Treatment × Position	0.9834	**0.0008**	0.7976

Table 4. 4. ANOVA table for crop yields.

Crop (Phase)	Wheat (1 and 2)	Flax (3)	Barley (4)
Effect		Yield (kg ha^{-1})	
ANOVA		*P* value	
Treatment	0.7590	0.6964	0.0576
Position	**<.0001**	0.6532	**<.0001**
Treatment × Position	**0.0187**	**0.0065**	**0.0212**
Site	**0.0077**	**0.0001**	0.4539
Site × Treatment	0.8122	0.5012	0.0654
Site × Position	0.6378	0.4693	**0.0297**
Site × Treatment × Position	0.7360	0.1103	0.6929

Table 4. 5. ANOVA contrasts for crop yields.

Crop (Phase)	Wheat (1 and 2)	Flax (3)	Barley (4)
Effect		Yield (kg ha^{-1})	
ANOVA		*P* value	
Contrasts:			
K_0 vs D_0	**<.0001**	0.8040	**0.0091**
K_0 vs K_{10}	**0.0095**	0.8982	0.1516
K_0 vs K_{20}	**0.0345**	0.2545	0.1869
K_0 vs K_{30}	**0.0002**	0.8376	0.2202
K_0 vs D_{10}	0.0881	0.2545	0.6811
K_0 vs D_{20}	0.7174	0.8208	**0.0107**
K_0 vs D_{30}	0.7498	0.2295	0.0714
D_0 vs K_{10}	0.0535	0.7070	0.2484
D_0 vs K_{20}	**0.0159**	0.1667	0.1410
D_0 vs K_{30}	0.4349	0.6506	0.1156
D_0 vs D_{10}	**0.0049**	0.3711	**0.0191**
D_0 vs D_{20}	**<.0001**	0.6352	**<.0001**
D_0 vs D_{30}	**<.0001**	0.1458	**<.0001**
K_{10} vs K_{20}	0.6242	0.3109	0.8402
K_{10} vs K_{30}	0.2470	0.9386	0.7660
K_{20} vs K_{30}	0.1003	0.3487	0.9166

Table 4. 6. Normalized yield data by crop phase and by site (A = Altamont; B = Bruxelles; M = Manitou).

Phase	1 (Wheat)			2 (Wheat)			3 (Flax)			4 (Barley)		
Site	A	B	M	A	B	M	A	B	M	A	B	M
Treatment												
K_0	0.71	0.73	0.65	0.52	0.44	0.39	0.66	0.73	0.23	0.17	0.16	0.34
K_{10}	0.82	0.70	0.86	0.61	0.37	0.39	0.84	0.57	0.50	0.14	0.33	0.31
K_{20}	0.79	0.79	0.77	0.68	0.51	0.61	0.69	0.49	0.42	0.44	0.44	0.61
K_{30}	0.73	0.89	0.72	0.69	0.47	0.67	0.58	0.29	0.50	0.57	0.27	0.47
D_0	0.73	0.75	0.79	0.73	0.47	0.79	0.74	0.30	0.61	0.37	0.28	0.36
D_{10}	0.57	0.49	0.51	0.64	0.49	0.80	0.57	0.26	0.55	0.07	0.40	0.12
D_{20}	0.56	0.39	0.46	0.67	0.38	0.50	0.62	0.55	0.43	0.18	0.29	0.15
D_{30}	0.41	0.37	0.37	0.56	0.39	0.59	0.61	0.54	0.54	0.07	0.13	0.09
Ratios												
K_0/D_0	0.97	0.97	0.82	0.71	0.94	0.49	0.89	2.43	0.38	0.46	0.57	0.94

4.4.2.2. Added topsoil treatments (K_{10}, K_{20}, K_{30})

In terms of crop performance, there were no significant differences in biomass among K_{10}, K_{20} and K_{30} treatments in any of the crop phases, despite significant ANOVA *p*-values in Table 4.3. Contrasts among the added topsoil treatments (Table 4.5) revealed all three treatments were significantly different from K_0 in the wheat phases but not significantly different from K_0 in the flax or barley phases and not significantly different from each other in any of the crop phases. K_{20} in the wheat phases was the only added topsoil treatment whose contrast with D_0 was significantly different. Normalized yield data across all sites (Table 4.6) showed a generally positive increase through the addition of topsoil, regardless of the depth added, that not only improved yields over K_0 (except at Bruxelles, flax phase) but also in 9 of the 12 site and phase scenarios, at least one of the added treatments (K_{10}, K_{20}, K_{30}) had a greater normalized yield than the corresponding yield in D_0.

4.4.2.3. Removed topsoil treatments (D_{10}, D_{20}, D_{30})

Wheat biomass (grain and straw) at $\alpha = 0.05$ had a significant position effect, where D_{10}, D_{20} and D_{30} had a significant decrease in total biomass from the other treatments (Figure 4.2). For flax, total biomass at $\alpha = 0.05$ produced a significant but complex site × treatment × landscape position effect ($P = 0.0016$), in which only K_{10} and D_0 at Altamont and K_0 and K_{10} at Bruxelles had significantly greater biomass yields than D_{10} at Bruxelles and D_{20} at Manitou. Graphical depictions of flax biomass suggest statistical differences among treatments would be of no practical significance if these values were accurate simulations of what would occur under field conditions, typically 1200 – 1500 kg ha^{-1} (Manitoba Agriculture, 2025). For barley, total biomass at $\alpha = 0.05$ produced no significant effects, although the graphical depictions would suggest numerical differences among treatments, but these are discounted because of the statistical analysis and increased variability in treatment response due to the outdoor growing conditions.

Removal of topsoil reduced yields, with the magnitude of reductions increasing as more topsoil was removed, with the exception of the Bruxelles site in the flax phase that was an artifact of the column construction. Wheat yields (Phases 1 and 2) were significantly different at $\alpha = 0.05$ by site, by position and by a treatment × landscape position interaction (Table 4.4). Yields from the Altamont site were significantly greater than those from the Bruxelles and Manitou in the wheat and flax phases. Yield contrasts between D_0 and D_{10}, D_0 and D_{20} and D_0 and D_{30} were all significantly different in the wheat and barley phases (Table 4.5). Yields from all crop phases for D_{10}, D_{20} and D_{30} were not significantly different from each other (Figure 4.3). Yields from D_{20} and D_{30} (Figure 4.3) were significantly less than yields for D_0, K_{20} and K_{30}, the numerically-highest yielding treatments. Phase 3 (flax) yields were significantly different at $\alpha = 0.05$ by site (Altamont significantly greater than both Bruxelles and Manitou) and as a treatment × landscape position interaction, but with different relative rankings for the highest-yielding treatments than those observed for wheat.

4.4.3. Soil moisture changes by site

4.4.3.1. Total water (TW) content

For ease of comparison among sites, soil layers and treatments, total water (TW) was used, realizing not all of this water would be available for plant uptake. Relative rankings in TW by treatment in the 0 - 30 cm depth of the soil columns throughout the growing season of each crop phase were similar for the Altamont and Manitou sites, with less TW in the Bruxelles columns (Figure 4.4).

The Altamont site demonstrated the clearest increase in TW as the depth of topsoil increased from K_0 to K_{30}, to the point where total water in the K_{30} treatment consistently exceeded that of D_0 control. TW levels for K_0 were consistently lowest for all crop phases. At Bruxelles, differences in TW between K_0 and D_0 were less pronounced, with D_0 consistently having the greatest total water over time in all crop phases. K_{10} and K_{30} had intermediate levels of TW, with K_{20} consistently having least amount of TW. This was unexpected, and suggests that this treatment may have been subject to bypass flow, which could have been remedied with additional column replication for soil moisture measurements. TW for K_0 was one of the lower levels for all crop phases. At Manitou, trends in TW by treatment were similar to that of Bruxelles, with D_0 consistently having the greatest total water, followed by K_{30}, with K_0, K_{10} and K_{20} all having similar, lower TW over three crop phases. At all sites and crop phases, TW levels for K_0 is less than D_0.

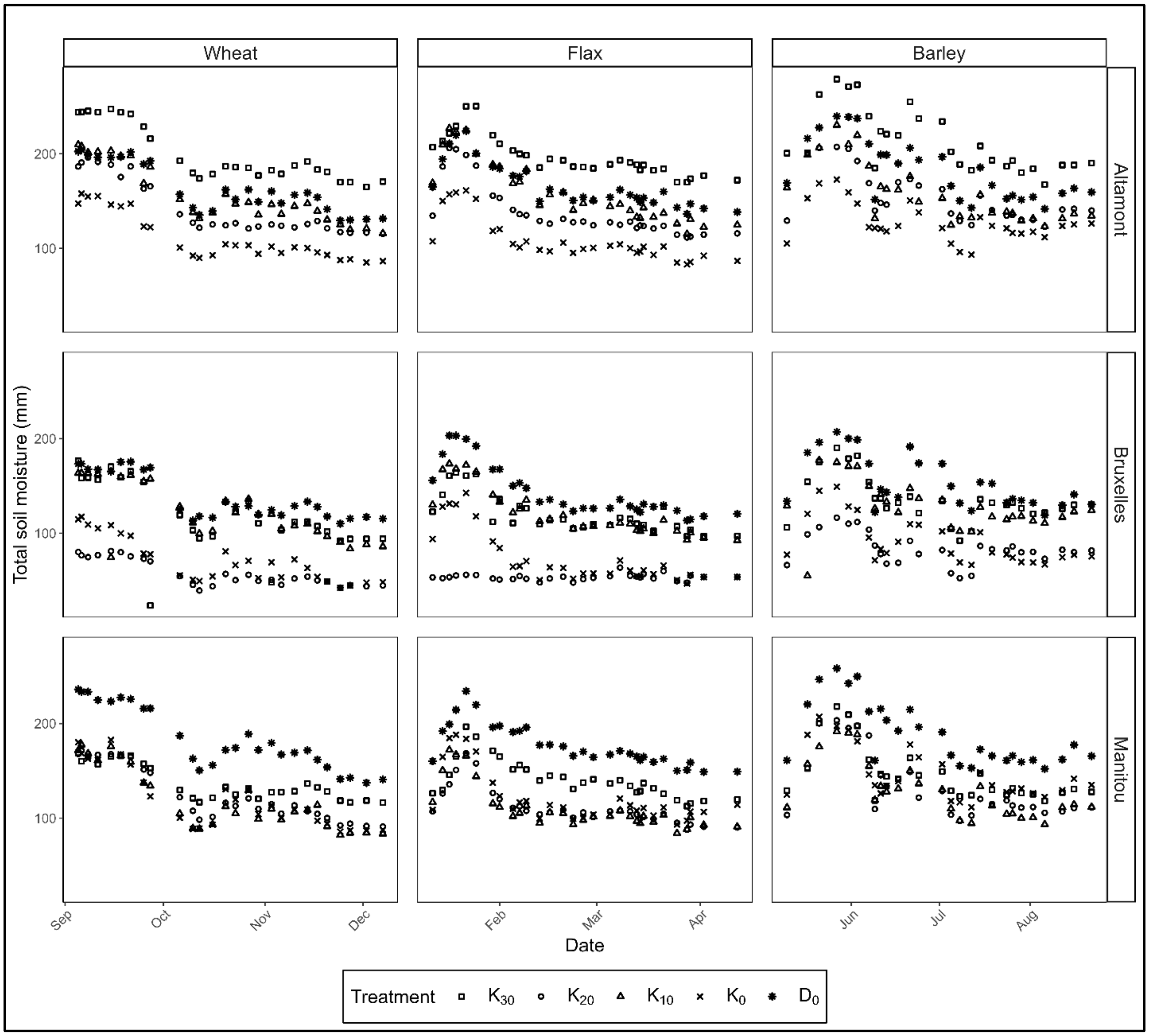

Figure 4. 4. Changes in total water (mm) at 0-30 cm depth, as affected by topsoil addition depth to the knoll cores and by site over wheat, flax and barley crop phases.

Changes in TW values where topsoil was removed resulted in even more stark differences than those observed where topsoil was added (Figure 4.5); only minor reductions in total water values occur in D_{10}; with progressively less TW in the D_{20} and D_{30} treatments. D_{20} and D_{30} TW values were more similar in the Manitou and Bruxelles sites than at Altamont, due to the decreasing subsoil water holding capacity from Altamont to Manitou to Bruxelles.

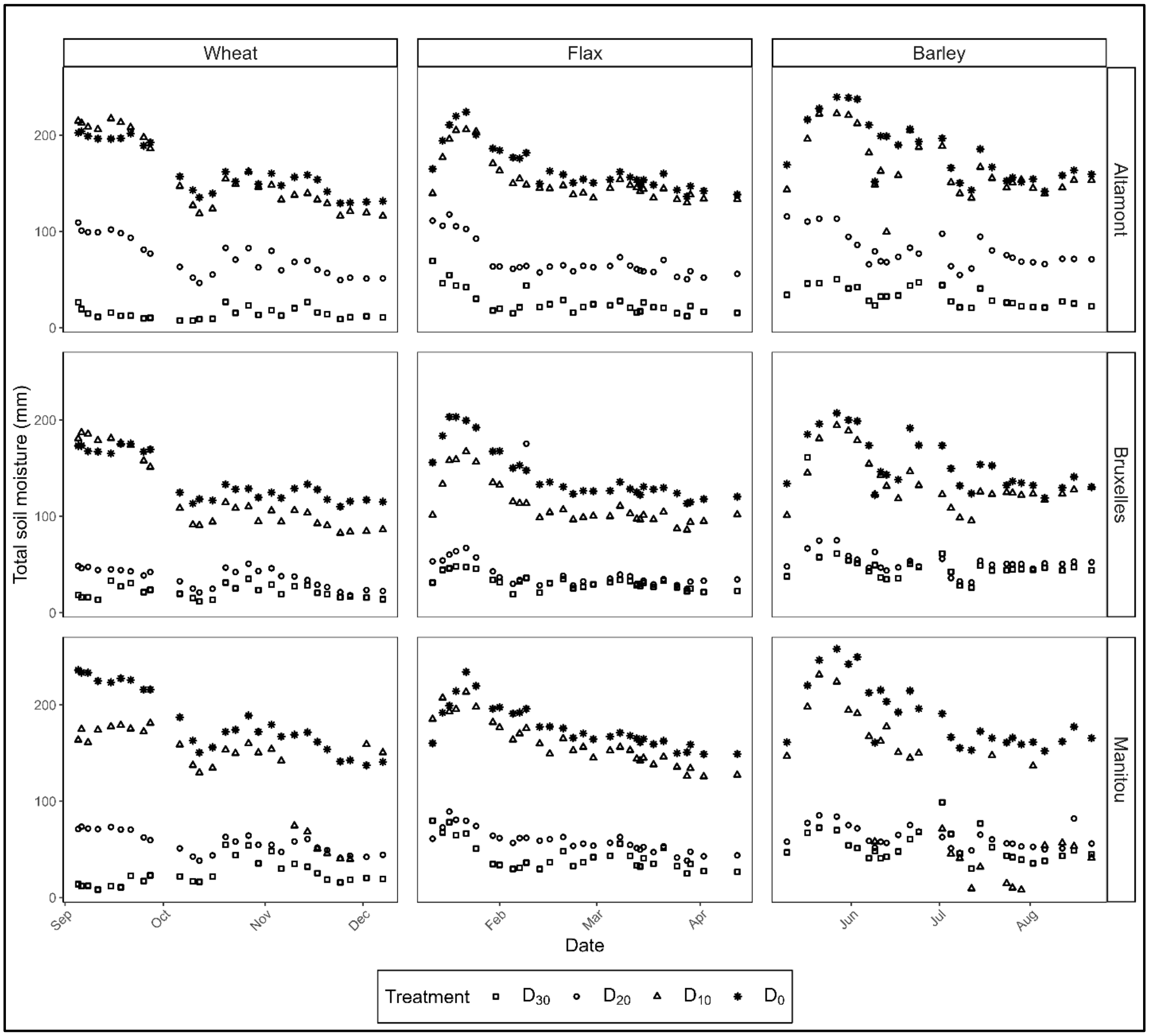

Figure 4. 5. Changes in total water (mm) at 0-30 cm depth, as affected by topsoil removal depth from the depression cores and by site over wheat, flax and barley crop phases.

For Phase 2 (wheat) and Phase 4 (barley) where soil moistures were measured at $\alpha = 0.05$, there was a significant date effect, treatment effect, and treatment × date interaction effect (Table 4.7). The main effects were significant in that total soil moisture varied according to sampling date, which generally declined throughout the growing season but temporarily increased after artificial watering or precipitation events. Treatment effects for TW in the top 30 cm of the column profiles were highest for K_{10}, K_{20}, K_{30} and D_0 and were all greater than TW for K_0 (Figure 2), as well as

D_{20} and D_{30} (Figure 3). The significant interactions indicated that these differences in soil moisture by treatment varied in their relative differences by sampling date (i.e. some treatments held more TW than others at certain sampling dates, but over time, these relative rankings often changed as moisture conditions changed).

For Phase 3 (flax), there were only significant main effects at $\alpha = 0.05$, but, like the two other phases, the treatment effects displayed significantly higher TW contents in K_{10}, K_{20}, K_{30} and D_0 than moisture contents in K_0, D_{20} and D_{30}. The absence of an interaction suggests these relative rankings in TW did not vary by date throughout the flax growing season (i.e. the relative rankings of TW were more consistent with flax than with wheat and barley).

Table 4. 7. ANOVA table for repeated measures of soil moisture

Crop (Phase)	Wheat (1 and 2)	Flax (3)	Barley (4)
Effect	---------------------------Total Water (mm)--------------------		
ANOVA		*P* value	
Numerical Date	**< 0.0001**	**< 0.0001**	**< 0.0001**
Treatment	**< 0.0001**	**< 0.0001**	**< 0.0001**
Treatment × Numerical Date	**0.0004**	0.8121	**0.0062**

4.4.3.2. Available water content

In Chapter 2, adding topsoil to eroded knolls produced a range of responses for SOC stocks when compared to the control knoll, according to site. SOC stocks increased significantly at Bruxelles, increased only numerically at Manitou and essentially did not increase at Altamont. Given the influence SOC is expected to have on AWHC, similar outcomes for the three sites are expected.

Differences in soil textures by site, landscape position and depth give rise to different amounts of available water (AW) holding capacity (Table 4.8). Even though Altamont was measured to be the most eroded of the three sites, both soil series at this site (Poyser at the knoll and Tellier at the depression) hold the most AW of the three sites at both landscape positions, masking crop productivity responses to added topsoil treatments. Differences between the AW of the 0-30 cm depth of unrestored soil columns (D_0 and K_0) revealed the Bruxelles site had the greatest difference in AW (17.1 mm), followed by Manitou (5.8 mm), with Altamont essentially having no difference in AW between landscape positions (0.4 mm). Therefore, the Bruxelles site showed the greatest potential for increasing AW through the addition of topsoil.

Table 4. 8. Soil moisture retention data by site and landscape position. Silica sand is at 40 cm. The FC and PWP values are numerically different for each site × treatment × location combination. (Number of samples = 24).

Site	Treatment	Treatment	Location	Depth (cm)	Porosity	Bulk Density (g cm^{-3})	FC (vol%)	PWP (vol %)	AW (vol %)	Total AW (mm)[1]
Altamont	control	D_0	depression	10	0.62	1.00	43.1	21.0	22.0	
				20	0.43	1.50	38.9	21.5	17.4	
				30	0.37	1.67	41.1	16.2	24.9	64.3
				40	0.43	1.51	37.1	13.4	23.7	88.0
		K_0	knoll	10	0.65	0.94	43.9	20.1	23.8	
				20	0.54	1.21	38.2	18.5	19.7	
				30	0.56	1.16	39.9	19.4	20.4	63.9
			sand	40	0.40	1.59	12.5	12.4	0.1	64.0
Bruxelles	control	D_0	depression	10	0.62	1.01	36.0	18.0	18.0	
				20	0.42	1.53	32.0	16.4	15.6	
				30	0.47	1.41	33.5	17.0	16.5	50.1
				40	0.48	1.38	32.8	14.4	18.4	68.5
		K_0	knoll	10	0.57	1.15	31.4	14.9	16.5	
				20	0.46	1.42	27.7	14.6	13.1	
				30	0.52	1.27	23.2	19.9	3.3	33.0
			sand	40	0.37	1.68	4.0	4.0	0.0	33.0
Manitou	control	D_0	depression	10	0.71	0.77	42.5	24.7	17.8	
				20	0.59	1.09	43.7	28.5	15.2	
				30	0.56	1.17	45.1	27.9	17.2	50.2
				40	0.52	1.27	45.7	24.9	20.7	70.9
		K_0	knoll	10	0.68	0.86	41.4	25.4	16.0	
				20	0.67	0.87	40.4	24.0	16.4	
				30	0.60	1.05	37.5	25.5	12.0	44.4
			sand	40	0.40	1.60	5.8	5.8	0.0	44.4

[1]Total AW presents sum of available water within either the top 30-cm of the soil column or the top 40-cm of the soil column (i.e., shaded values).

Differences in AW were more subtle than TW and varied with depth. Soil properties in D_0 treatments were more conducive to improved crop performance than K_0, primarily by the increased TW and extended periods of AW. AW status of added topsoil treatments was compared by site to D_0 to detect increases in AW holding capacity. At Altamont, AW for K_0 and D_0 are similar in the wheat phase at 10 and 20 cm. More AW is present in D_0 than K_0 at 30 and 40 cm in all crop phases and occasionally at 10 cm depth in the flax and barley phases (Figure 4.6). K_{30} is similar to D_0 at 10 cm depth, with no data available for K_{20}. At 20 and 30 cm depths, K_{10}, K_{20} and K_{30} have similar AW as D_0, but K_{30} has more AW than D_0 at 30 cm during the flax and barley crop phases. AW for K_{10} and K_{20} exceeded that of D_0 at 40 cm. Therefore, K_{30} stores more water at shallower depths in the profile.

At Bruxelles for all crop phases, AW values were similar for K_0 and D_0 at 10 cm, with more AW for K_0 at 20 cm and more AW for D_0 at 30 and 40 cm (Figure 4.7). AW for all added topsoil treatments and crop phases are similar at 10 cm; AW for K_{10} and K_{30} exceeds D_0 at 20 cm but is less than D_0 at 30 and 40 cm. AW for K_{20} is similar to D_0 at all depths and crop phases except at 30 cm where AW is less than for D_0. Similar to Altamont, K_{10} and K_{30} store more water at shallower depths than K_{20} or D_0.

At Manitou, AW values were similar for K_0 and D_0 at 10, 20 and 40 cm depths in all crop phases, but with increased AW for D_0 at 30 cm (Figure 4.8). For Manitou, the AW for the added topsoil treatments was similar to that of D_0 at 10 and 20 cm, and less than D_0 at 30 cm. Any increases in AW by treatment were more modest and short-lived at 40 cm than the other sites. In terms of AW, moisture values for all sites were often below PWP when measured, and rarely measured above FC.

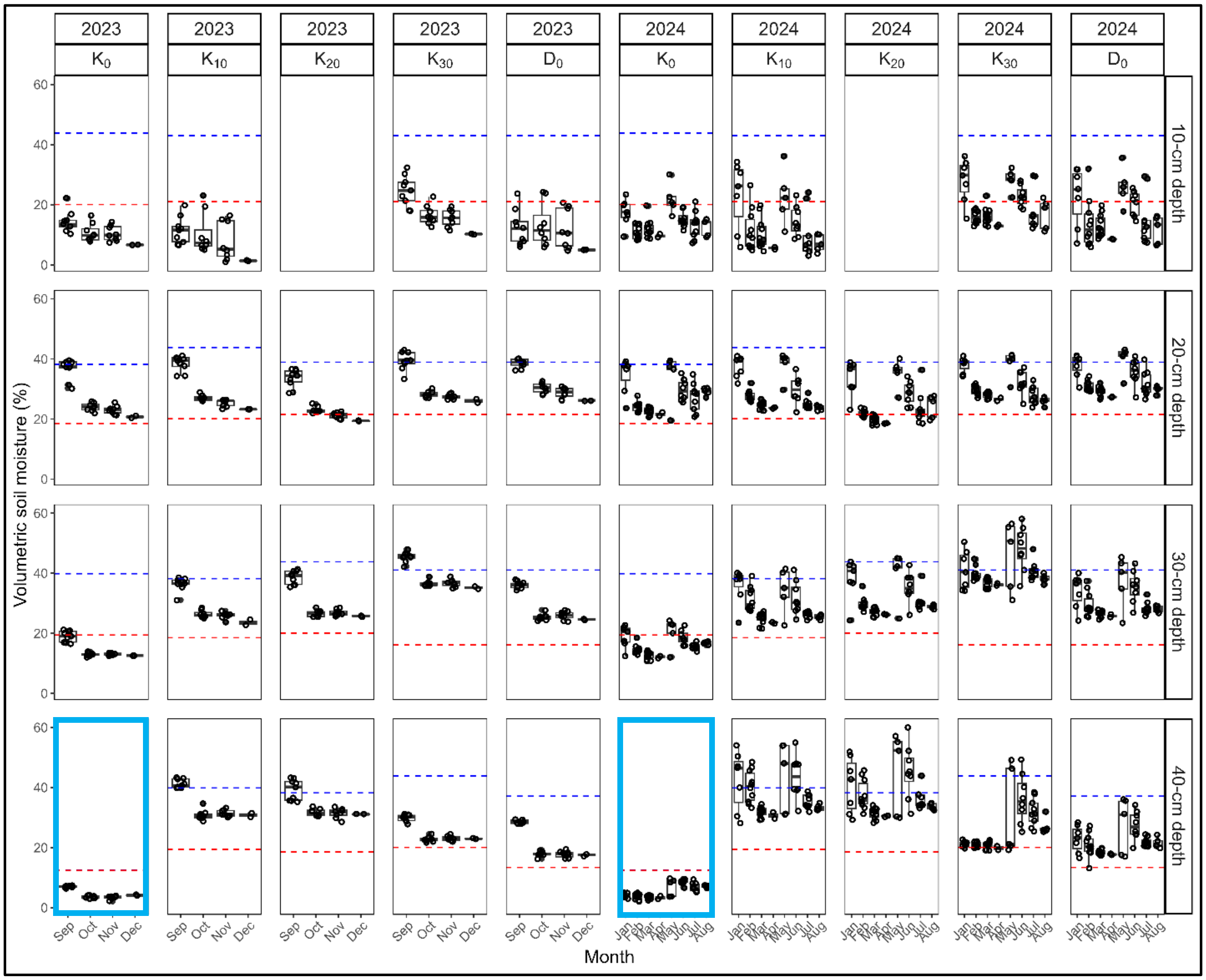

Figure 4. 6. Boxplot distributions of volumetric soil moisture content by depth (%) in experimental runs 2 (2023), 3 and 4 (2024) in Altamont knoll cores where topsoil was added. Blue dashed lines represent moisture content at field capacity; red dashed lines represent moisture content at wiling point. The blue outline represents depths of soil columns filled with silica sand.

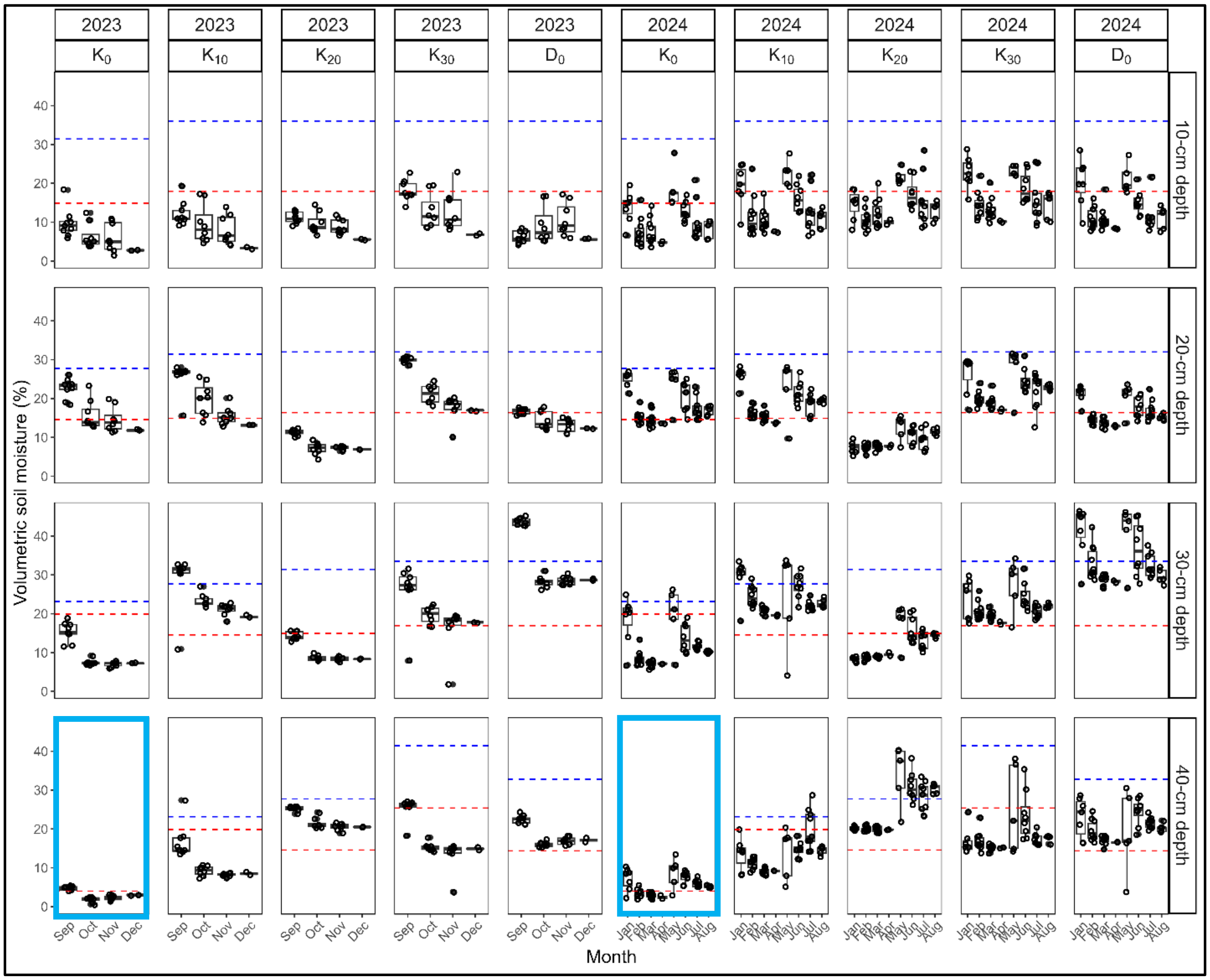

Figure 4. 7. Boxplot distributions of volumetric soil moisture content by depth (%) in experimental runs 2 (2023), 3 and 4 (2024) in Bruxelles knoll cores where topsoil was added. Blue dashed lines represent moisture content at field capacity; red dashed lines represent moisture content at wilting point. The blue outline represents depths of soil columns filled with silica sand.

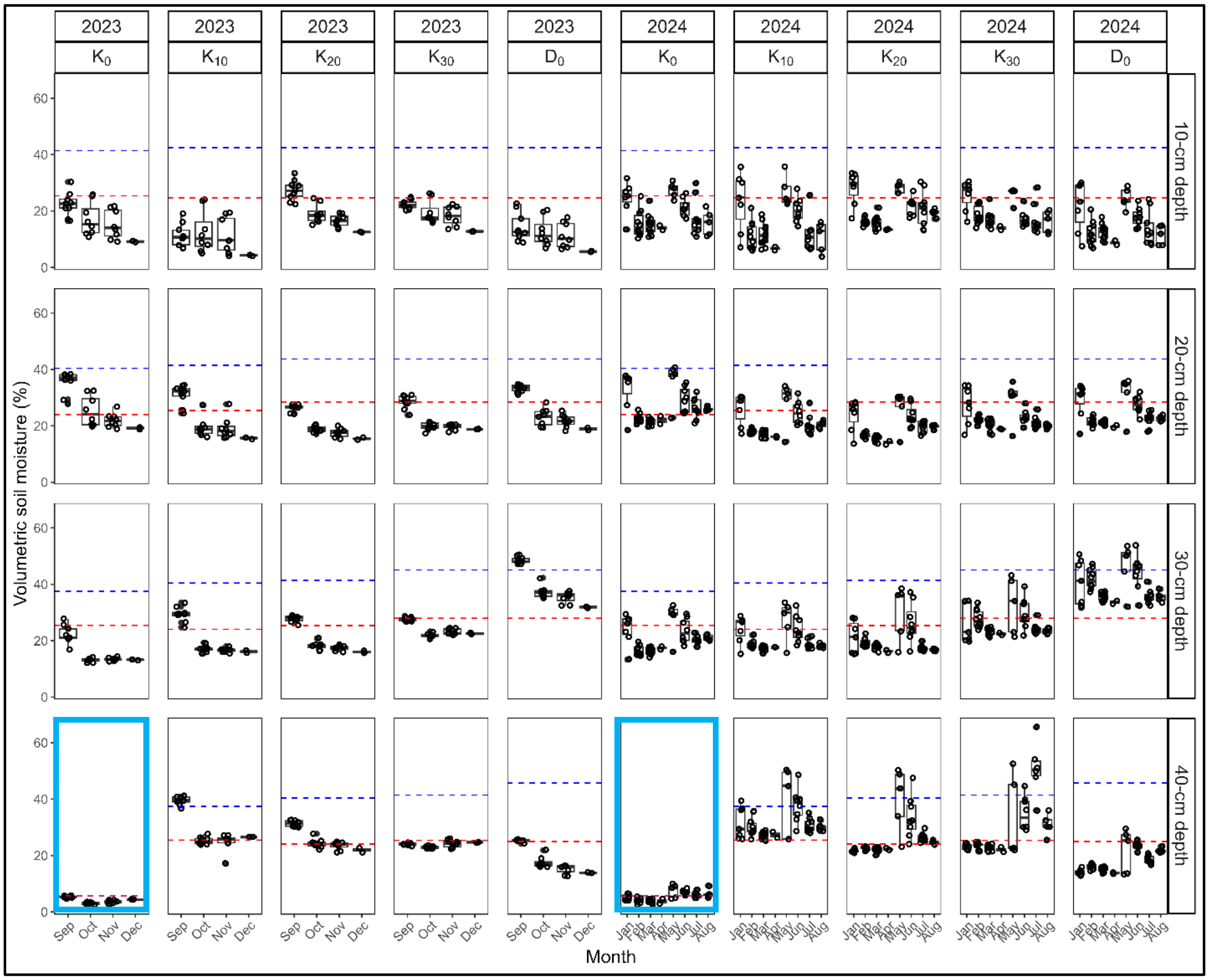

Figure 4. 8. Boxplot distributions of volumetric soil moisture content by depth (%) in experimental phases 2 (2023), 3 and 4 (2024) in Manitou knoll cores where topsoil was added. Blue dashed lines represent moisture content at field capacity; red dashed lines represent moisture content at wilting point. The blue outline represents depths of soil columns filled with silica sand.

With essentially no water-holding capacity in the sand layer, the AW in the removed topsoil treatments (Figures 4.9 – 4.11) was a function of the overall depth of natural remaining subsoil. D_0 control contained soil water that was occasionally in the AW range at 10 cm and consistently in the AW range at 20, 30 and 40 cm. The removed topsoil treatments mimicked the D_0 moisture content at depths in which the sand layer is absent; therefore, AW in D_{10} behaved similarly as D_0

at 10, 20 and 30 cm. D_{20} was similar to D_0 at 10 and 20 cm depths. D_{30} was similar to D_0 at the 10 cm depth only.

An anomaly occurred where D_{20} and D_{30} had more available water retained in the surface layers for longer periods of time than there was in the added topsoil, which did not receive sufficient water to increase yield production beyond the other treatments. The different treatment rankings may be partially explained by the shallow rooting depth of flax (Flax Council of Canada) and the artificially-elevated soil moisture content immediately above the sand layers in the treatments where the sand layer comes close to the surface (i.e., the “check-valve” effect) (Berdouki et al., 2024).

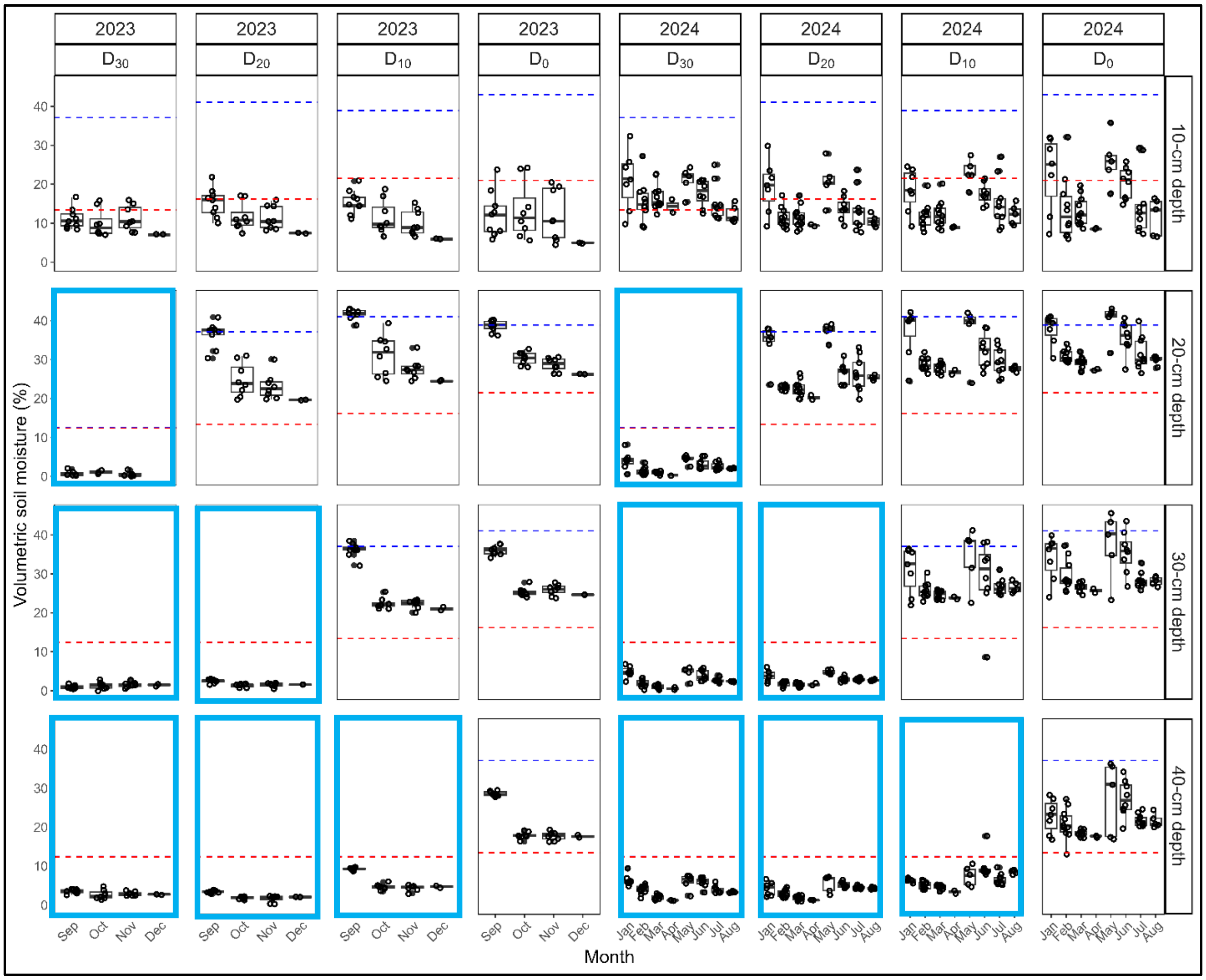

Figure 4. 9. Boxplot distributions of volumetric soil moisture content by depth (%) in experimental phases 2 (2023), 3 and 4 (2024) in Altamont depression cores where topsoil was removed. Blue dashed lines represent moisture content at field capacity; red dashed lines represent moisture content at wilting point. The blue outline represents depths of soil columns filled with silica sand.

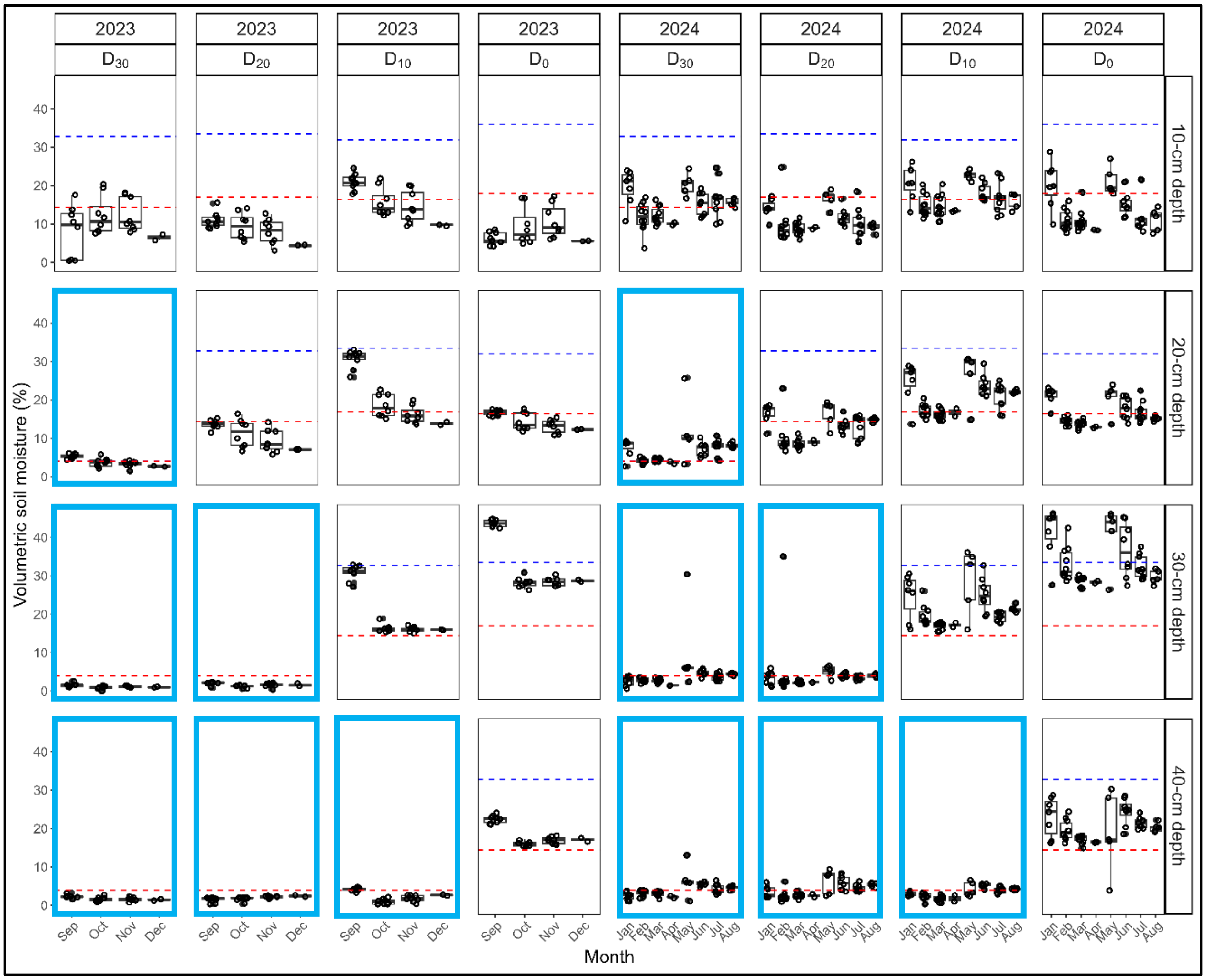

Figure 4. 10. Boxplot distributions of volumetric soil moisture content by depth (%) in experimental runs 2 (2023), 3 and 4 (2024) in Bruxelles depression cores where topsoil was removed. Blue dashed lines represent moisture content at field capacity; red dashed lines represent moisture content at wilting point. The blue outline represents depths of soil columns filled with silica sand.

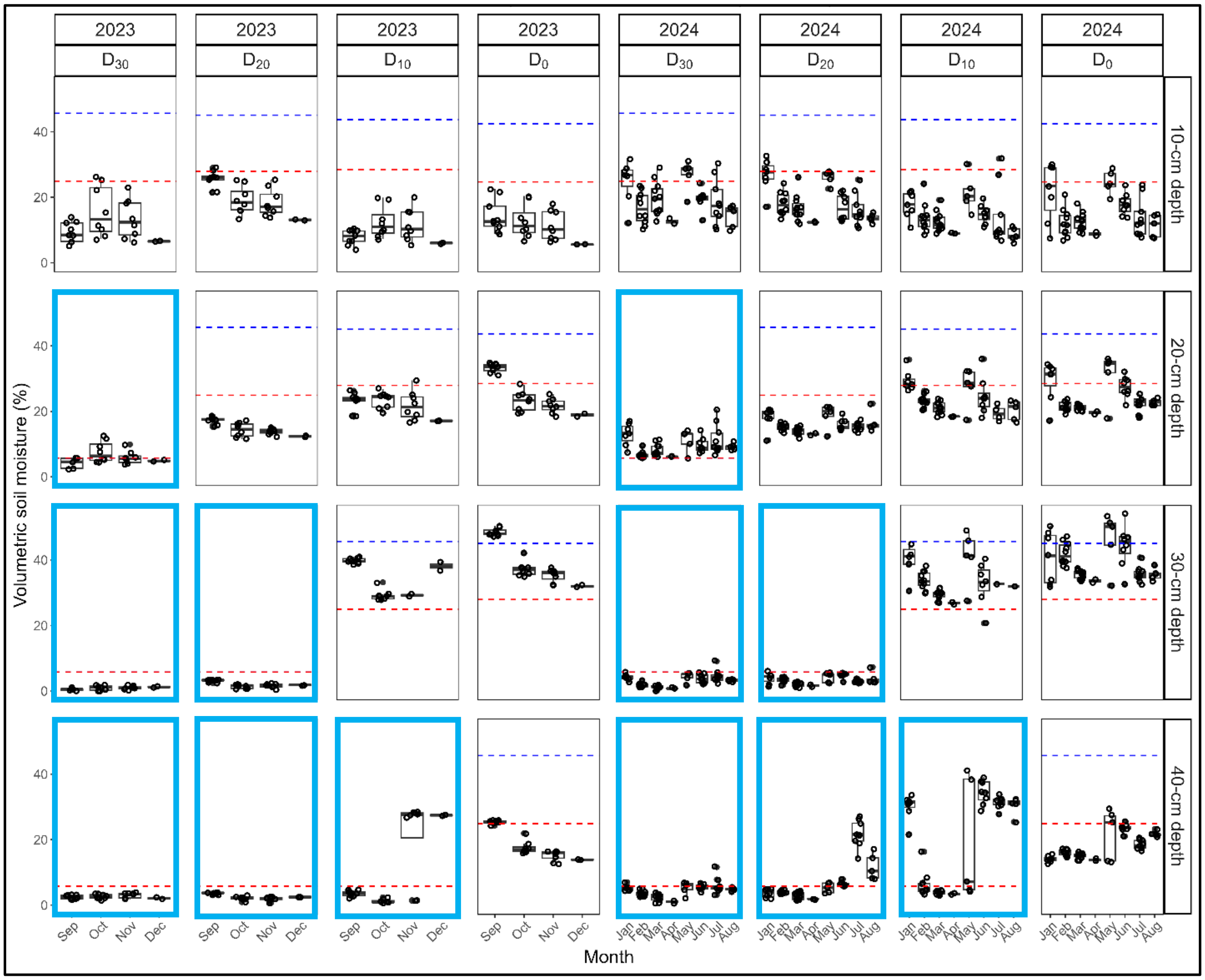

Figure 4. 11. Boxplot distributions of volumetric soil moisture content by depth (%) in experimental runs 2 (2023), 3 and 4 (2024) in Manitou depression cores where topsoil was removed. Blue dashed lines represent moisture content at field capacity; red dashed lines represent moisture content at wilting point. The blue outline represents depths of soil columns filled with silica sand.

4.4.4. Plant root simulator probes

Difficulties in establishing the PRS® probes early in run 2 of wheat due to compacted soil conditions required the use of a small drill with a 1-cm diameter bit to open up the soil and insert the probes into the soil. Despite best efforts to backfill and pack the holes with the excavated topsoil from the drill hole, it was difficult, if not impossible, to create sufficient soil contact with the probes to obtain meaningful data. As a result, these data are not reported here.

4.5. Discussion

The purpose of conducting a column experiment was to allow for removal of landscape features (elevation, slope, runoff) and management factors that would otherwise result in site or random differences when conducting these studies in the field. However, there are also other artifacts that are created in the column experiment that need to be highlighted because of their potential confounding effects and greater propensity to produce type II statistical errors (Montesinos, 2024). Other pot studies research on soil erosion simulated topsoil removal by dilution with subsoil (Pehlivan et al., 2025; Gao et al., 2015) to reflect the mixing of subsoil with topsoil via tillage during the intermediate phases of erosion. The intent of this study was to determine the depth of topsoil added to an eroded knoll that would offset the negative effects of erosion, and it was believed to be a more accurate measurement if the core layers and their features be left intact wherever possible to simulate the conditions of a no-till environment with minimal mixing of soil by tillage. Previous greenhouse pot studies on various field crops have been conducted with wheat (Farooqi et al., 2024), barley (Konate et al., 2020) and flax (Goudenhooft et al., 2018)

ANOVA revealed some obvious effects from landscape and site. Treatment effects, some of which are interactions, were only are significant in certain crop phases. This shows that some effects under field conditions only are evident in certain site-years, due to environmental and management conditions that may accentuate certain effects while masking others. The outdoor growing conditions of the barley phase (natural light; more aggressive watering through natural precipitation in May and June, followed by dry conditions in July and August) highlighted yield differences from the previous phases; treatments where topsoil was added to knolls (K_{10}, K_{20} and K_{30}) had a significant yield increase over both untreated knolls K_0 and the depression treatments where topsoil was removed (D_{10}, D_{20} and D_{30}.)

Light intensity and photoperiod used in the study was low compared to natural sunlight despite the doubling of the number of lights used after the first cropping phase. However, it was determined to be acceptable based on greenhouse fruiting vegetable production ranges from 100 – 300 µmol m^{-2} s^{-1} (Hao et al., 2018) and 14 – 17 h (Hao, 2016), respectively. Working with very high densities of wheat (2000 plants m^{-2}), Salisbury et al. (1987) observed biomass production to increase almost linearly with increasing light intensity from 400 – 1700 µmol m^{-2} s^{-1}. The main outcome from growing field crops in greenhouse conditions is producing taller plants (Goudenhooft et al., 2018) but Kocak (2024) found flax plant height was considerably reduced in the greenhouse. Limiting water supply to sweet pepper greenhouse production reduced total fruit production and marketable fruit production when compared to optimal crop water needs (Fernández et al., 2005).

In China, Gao et al. (2015) used Mollisol soils from midslope to upslope positions of the landscape, removing topsoil from the surface 20 cm of soil and mixing with the subsoil below. Crop response was a 5% reduction in biomass and a 6% reduction in yield per 10 cm soil loss. By contrast, in this study, topsoil was removed from depressions, or lower-slope positions, and added to the upslope (knoll) position. Crop biomass response was an approximate 10% reduction per 10 cm of topsoil removed (wheat only). Using normalized crop yields produced a wide range of responses, depending on crop type, site, treatment and their interactions (on average, a 17%, 15% and 23% reduction in yields per 10 cm topsoil removed for wheat, flax and barley, respectively). Conversely, adding topsoil did not significantly increase crop biomass and increased only barley yields on average by 83% per 10 cm of soil added (though the direct contrast of K_0 and K_{20} was not significantly different).

K_{30} provided the largest increase in TW, at times exceeding that of D_0, but this did not translate into significant increases in crop performance, likely due to limited available water from the restricted watering regimes. These differences were reduced when AW was considered and in light of the limited column depths. While it produced differences when considering the 0-30 cm depth, these differences become less important to crop performance once the crop is established and the roots extend further into the soil profile. Wen and Easter (1987) also noted the dominant effect of subsoil, rather than topsoil, on AW.

The critically low AW measurements at 10 cm depths were not an accurate reflection of the true soil moisture status throughout the growing periods at this depth; if it were, the plants would have never germinated, established and survived to maturity. This is likely a function of limited moisture sampling events, and high porosity/low bulk density at this depth due to lack of cultivation or packing of soil materials, respectively. When compared to bulk density data at 5 – 15 and 15 – 30 cm depths from 2023 field samples, which were on average 14% higher, suggest the presence of macropores within the largely undisturbed soil layers in the columns. Higher than expected infiltration rates (not measured in the columns) were possibly the result of macropore flow within the intact cores and possible bypass flow between the column sidewall and soil core. With surface soil textures at most sites and locations having a medium-heavy texture that could be subject to modest shrink-swell phenomena under changing soil moisture conditions, bypass flow may have occurred when soil columns dried out over time. Frequent monitoring of soil moisture conditions, early warnings of dry conditions from guard columns and subsequent watering were expected to be adequate measures to ensure columns did not become too dry to support crop growth to reach maturity.

Based on the AW data, water appeared to infiltrate further and faster into the Manitou soil columns than the other sites, even though the Bruxelles site has more sand in the natural soil cores layers than the other two sites. Field data from the previous soils chapter indicated the mean water infiltration rate of the Manitou depression topsoil was 46 cm hr^{-1} versus 35 cm hr^{-1} for Altamont and 24 cm hr^{-1} for Bruxelles (though not statistically significantly different). Much of the excess water may have passed out the bottom of the Bruxelles columns (though water leaving the columns was not measured) whereas the Manitou retained moisture at 40-cm depth, while Altamont retained the most of the added water at the 30- and 40-cm depths.

Limitations of AW holding capacity of the columns due to the 60-cm column depths and the addition of silica sand layers accentuated the differences among the depth of topsoil in each column and each site. Only real treatment differences within landscape positions occurs within 0-30 cm layer (due to 15-20 cm of topsoil removed from depressions and subsequently added to the knolls). The intent was to increase the amount of AW in the 0-30 cm layers through the addition of topsoil, but under “real world” (dryland) growing conditions where moisture is allowed to become limited, increases in water-holding capacity did not always translate into increases in crop productivity, as the shallow depths were the first to dry out due to evaporation, infiltration, or runoff and may not be available for crop-water utilization.

Removing topsoil had the opposite effect on TW as adding topsoil, with none to minor reductions in total water from D_0 to D_{10}, and major reductions for D_{20} and D_{30}. D_{20} and D_{30} treatments were inferior to the other treatments in the amount of total water held in the 0 - 30 cm depth, which is likely an artifact of the column treatment design, and would not be experienced in the field, as 20 - 30 cm of the soil cores were replaced with silica sand, which offered negligible water holding capacity. Additionally, removing topsoil in the field would often result in concave artifacts that would hold ponded water and offset differences in total water stored in these soils.

4.6. Conclusions

Based on the yield, biomass and soil moisture data (TW and AW) collected over 4 phases of crop growth studies from soils collected from two landscape positions at three sites, adding 10-20 cm of topsoil (K_{10} and K_{20}) produced the most consistent, significant improvements to crop performance from the eroded knoll checks (K_0) among all sites, often not significantly different from crop performance observed in the higher-productivity control depression with no topsoil removed (D_0). The most effective topsoil addition treatments may vary by site, the crop grown and the growing conditions in the year of observation. Though adding 10 cm of topsoil (K_{10}) may be adequate under certain scenarios or when topsoil supply is limited, a range of added topsoil depths (K_{10} – K_{20}) may be suitable as a general recommendation due to varying soil properties and crop responses. Simultaneously, removing 10 cm of topsoil from the depressions (D_{10}) resulted in the least damaging yield reductions at all sites while providing a source of topsoil to restore productivity on eroded knolls. The magnitude of these effects varies depending on the crop grown and growing conditions, but the overall trends are relatively consistent.

Relative gains in yield from topsoil addition versus relative yield losses from topsoil removal suggest soil landscape restoration is a promising activity at restoring crop productivity on eroded landscapes; the details, however, are important in determining the expected responsiveness of the site and the depth of topsoil to remove and add in order to provide the most efficient overall benefit.

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Chapter 5

Synthesis of findings

5.1. Synthesis of findings

The findings of the previous chapters can be examined in progression. In Chapter 2, using ^{137}Cs as an effective tracer for identifying and quantifying erosion and topsoil movement within select landscapes, it was shown that soil landscape restoration was able to restore eroded knolls to previous non-eroded states (Table 5.1). Similarly, for soil organic carbon, soil landscape restoration was able to bring back SOC levels on eroded knolls close to what would be found in non-eroded landscapes. There was no significant change in infiltration rates from added topsoil (in our sites, moving topsoil did not significantly change soil textures, as confirmed by laser diffraction analyses) and only minor changes in proportion of water-stable aggregates from added topsoil measured in the year following soil landscape restoration.

Table 5. 1. Assessment of key soil properties and changes resulting from landscape restoration.

Site	Mean Erosion Status ($Mg\ ha^{-1}\ yr^{-1}$)		Mean ^{137}Cs inventories ($Bq\ m^{-2}$)		Mean SOC stocks ($kg\ C\ m^{-2}$)	
	Control Knoll	Control Depression	Control Knoll	Added Knoll	Control Knoll	Added Knoll
Altamont	21	-34	659	2206	12.0	11.8
Bruxelles	17	-25	746	1462	11.2	19.0
Manitou	15	-9	833	1670	9.7	14.0

SOC stocks increased numerically, if not statistically, with added topsoil, but may not always convert into increased crop biomass and crop yields, based on the distribution of SOC within the soil profile. The importance of near-surface SOC cannot be overstated, but the changes made to overall available water holding capacity (AWHC), when measured over the rooting zone of the soil profile, may not always result in increased AWHC that is important during crop germination and early establishment.

In Chapter 3, the most important impact to observe was the potential increase in crop biomass and yield from the addition of topsoil to eroded knolls (Table 5.2). Out of the 12 site-years, only two site-years showed a significant, positive treatment response for biomass on the knolls and only four site-years showed a significant, positive grain yield increase from the practice of soil landscape restoration on eroded knolls. For biomass, these responsive site-years were Altamont in 2021 (wheat) and Bruxelles in 2024 (wheat). For yield, these were three site-years at Bruxelles 2022-2024 (oats, canola, wheat), and one site-year at Altamont in 2022 (canola). Moving topsoil uphill also modestly increased already-high fall soil test values of Olsen P, but would not be considered sufficient to change fertilizer recommendations from previous management systems (Table 5.3). By contrast, ammonium-N and nitrate-N combined as plant available N approximately doubled in concentration from the addition of topsoil, similar to values measured by Schneider et al. (2023).

Table 5. 2. Summary of crop responses (biomass and yield) by site and by year.

Site		2021	2022	2023	2024	Comments
Altamont	Landscape effect (depression > knoll)	Both	Both	None	None	
	Treatment effect – depression (removed < control)	Both	Yield only	None	Both	Wetness artifacts
	Treatment effect – knoll (added > control)	Biomass only	Yield only	None	None	Variable
Bruxelles	Landscape effect (depression > knoll)	Yield only	Biomass only	Biomass only	None	
	Treatment effect – depression (removed < control)	Yield only	None	None	None	Minor – no drown outs
	Treatment effect – knoll (added > control)	None	Yield only	Yield only	Both	Consistent
Manitou	Landscape effect (depression > knoll)	Both	Both	Both	None	
	Treatment effect – depression (removed < control)	None	None	None	None	Minor – no drown outs
	Treatment effect – knoll (added > control)	None	None	None	None	Unresponsive

*The landscape effect is based on the assumption that total biomass and/or crop yield in the depression (D) is greater than those on the knoll (K).

The overall premise of applying soil landscape restoration as a sustainable soil management practice was that, if successful, yield increases on hilltops with topsoil added would be greater, and longer lasting, than yield decreases in topsoil removal from depressions. Assuming equal areas of hilltops and depressions are affected, combining total yield changes in both areas from the four responsive site years resulted in an overall net gain in yield at three of the responsive site-years (all at the Bruxelles site). If productivity in depressions with removed topsoil is expected to recover over time and hilltops with added topsoil maintain their increased productivity over time, the net benefit to the landscape as a whole will be positive for the long-term, but this needs to be verified with continued, longer-term studies.

Table 5. 3. Summary of expected versus measured outcomes of various soil and crop productivity factors.

Factor	Expected (literature)	Measured
AWHC	1% increase in SOC = 2 – 5% increase in AWHC (Hudson, 1994)	From -2.3 to 2.5% AWHC increase by volume (Table 3.5); From 0.4 – 17.1 mm increase (Table 4.8)
Crop Biomass	12 – 40% increase (Schneider et al., 2021)	22 – 42% increase; significant 2 out of 12 site-years (Table 3.3)
Crop Yield	12 - 133% increase	21 – 58% increase; significant 4 out of 12 site-years (Table 3.4)
Fall Olsen P	From control to rehabilitated at crest: from 9 to 19 ppm (0-15 cm); from 3 to 8 ppm (15-30 cm) (Schneider et al. 2023)	From control knoll to added knoll: from 42 to 48 ppm (0-15 cm) from 23 to 32 ppm (15-30 cm) (Figure 3.15)
Fall Plant Available N ($NH_4 + NO_3$)	From control to rehabilitated at crest: from 25 to 47 ppm (0-15 cm); from 17 to 25 ppm (15-30 cm) (Schneider et al., 2023)	From control knoll to added knoll: from 24 to 43 ppm (0-15 cm) from 11 to 26 ppm (15-30 cm) (Figure 3.14)
Infiltration	25× faster where topsoil was added - convex upper backslope only) (Schneider et al., 2023)	No significant change with added topsoil (Table 2.7)
SOC	From 12 to 35 g kg^{-1} (0-15 cm depth) (2.8× increase) (Papiernik et al., 2009) From 13 to 27 g kg^{-1} (0-15 cm depth) (2.1× increase) (Smith, 2008)	From 19 to 29 g kg^{-1} (0-15 cm depth) (1.5× increase)
Water-Stable Aggregates	Increased 19% with added topsoil (Schneider et al., 2023)	Only a significant decrease with removed topsoil (Table 2.6)
Yield Ratio Target (knoll ÷ depression)	70 – 80% (Zvomuya; Lobb)	80 – 94% (1 site, 3 years) (Table 3.4)

In Chapter 4, analysis of crop response to crops and watering under controlled growing conditions indicated that adding 10 - 20 cm of topsoil, while removing 10 cm from donor areas, would be the most effective means of increasing yield potential of eroded hilltops. Using cereal crops (wheat and barley) resulted in more significant and responsive outcomes than growing flax; adequate watering/rainfall ensured a significant, positive crop response; and differences in crop responses varied by site (soil type), in that the most eroded site (Altamont) demonstrated the most potential benefits from the implementation of landscape restoration practices, but in practice, it was the

Bruxelles site that responded most effectively to soil landscape restoration because of its limited AWHC and its subsequent increase from the addition of topsoil on the eroded knolls. Therefore, soils with loam or coarser textures may be more likely to respond positively to soil landscape restoration than heavier-textured soils.

Overall, for the three site-years at Bruxelles, soil landscape restoration as a Beneficial Management Practice (BMP) looks very promising because the positive yield responses to adding topsoil on eroded knolls are greater (significant) than the yield reductions (non-significant) from removing topsoil from the depressions. What remains to be understood more completely is how to ensure the above results continue over the long term with regular frequency at sites like Bruxelles, and how to encourage such a response (if possible) at less-responsive sites that behave like Altamont or Manitou.

This project received its initial funding through the Manitoba Wheat and Barley Growers Association (now the Manitoba Crop Alliance) to examine the soil and crop responses to the practice of soil landscape restoration, as a subset of a larger project that addressed extremes of moisture in western Canadian (Manitoban) crop production systems. It was paramount to draw attention to variable landscapes where extremes of moisture (drought and excess) are often exhibited simultaneously, to better understand carbon, water and nutrient dynamics and to offer management strategies that reduce, if not eliminate, these limitations so that a land parcel can managed more uniformly. Increasing the uniformity of management lowers production costs, increases the ease of predicting crop responses and creates a more resilient production system in the face of abiotic stresses whose frequency, duration and magnitude are difficult to predict.

5.2. Limited number of site-years responding positively to soil landscape restoration

There are likely several reasons for the lack of responses at Altamont and Manitou during the 2021-2024 study period: 1) Drier-than-normal precipitation in the years 2021, 2023 and the latter part of 2024 prevented any increase in water storage capacity from the addition of topsoil; 2) Crops such as canola, with a 360 - 530 kg ha^{-1} (6-9 bu ac^{-1}) yield increase (2 site-years out of 12), and soybean (non-significant) are less yield-responsive, or more difficult to establish, than cereals. One site-year was a wheat crop with a 1560 kg ha^{-1} (23 bu ac^{-1}) yield increase, and another site-year was an oat crop with a 1380 kg ha^{-1} (32 bu ac^{-1}) yield increase on newly added topsoil, which may still possess less-than-ideal seedbed characteristics (i.e. too high or too low BD and porosity); and 3) Despite the Altamont site showing the most *potential* for a positive crop response under controlled growing conditions of the column experiment, under field conditions this did not materialize due to factors such as: extremes in soil moisture exhibited at both the knoll (too dry) and depression (too wet) positions. Despite these moisture extremes, negligible differences in AWHC between landscape positions, and thus the addition of topsoil, may be masked by high weed pressure and the continuation of conventional tillage at this site.

By contrast, the Manitou site (similar to the moderately-eroded site in South Dakota in Schneider et al. (2023)) did not have a crop response to soil landscape restoration but was not masked by issues arising from weeds. Instead, this site has a history of manure applications from the 1980s and 1990s that likely elevated Olsen P values on the knoll position, which would mask treatment effects of crop responses when moisture for crop growth is sufficient. When moisture is limited, increases in the AWHC due to soil landscape restoration may not be sufficient to sustain a growing crop to capitalize on the luxuriant nutrient levels available in the soil.

More site-years of crops data are required for increased confidence in measuring positive responses to soil landscape restoration over a range of sites, crops and weather conditions. While initially disappointing, this should not be surprising, as overcoming the negative effects of erosion has been a long-standing issue, being difficult to assess, measure and quantify, with positive effects to crop production rarely, if ever, responding consistently under variable field, weather and management conditions.

5.3. Sources of error and limited measurements

In Chapter 3, soil moisture sampling four times throughout the growing season may not have been sufficient to capture the full extent of AW present for the growing crop, given the high propensity for evaporation, runoff and deep percolation following precipitation events. By the time manual measurements of soil moisture were collected, much of the water was either taken up by the crop for positive outcome but not documented, or lost so that maximum water storage from additional topsoil and organic carbon/organic matter was not realized. Missing from these trials, which could easily be remedied in future research, is to conduct continuous soil moisture monitoring in real time with automated equipment, as research budgets allow. Enhanced monitoring of soil moisture by landscape position and by treatment would allow for comparisons of water use efficiencies over the growing season.

In Chapter 4, soil moisture conditions within 10 cm of soil surface may be too variable and "noisy" to be reliable indicators of soil moisture trends over time. It is important to keep soil moist at the shallowest depths until the crop is established and the root zone can access water beyond 10 cm. This is of interest because this depth is within the layer of added topsoil; if soil moisture cannot be influenced because of added topsoil and SOC, then why do it? Or, is it just as important to add topsoil to eroded knolls *and* ensure surface moisture is conserved by reducing evaporation losses with added crop residues?

Also limiting is the number of measurements taken to calculate FC, PWP and ultimately the AWHC of the various soils. In some cases, the AWHC by recently-added topsoil did not always increase, let alone sufficiently increase, to carry a growing crop through to maturity and meet or exceed yield/biomass targets, because precipitation events are rarely optimum in the amount and timing of water provided.

We did not always make the sponge sufficiently bigger, and even when we did, we did not do anything to ensure it was filled, and stayed full, of available water!

Changes in bulk density and porosity through the movement and redistribution of topsoil likely affected the relative FC and PWP values, resulting in AWHC increases in only certain scenarios. Reductions in water holding capacity likely could be reversed over time using various practices, such as tillage or cropping strategies, that alter soil structure, bulk density and porosity to ensure AWHC increases over time.

Soil landscape restoration laid the foundation to improved soil health and increased productivity, but some sites may need "stacking" of additional moisture conservation management practices employed to ensure a positive crop response over time.

5.4. Commercializing the practice of soil landscape restoration

It is valuable to review the recommendations made by Lobb and Li (2024):

1. The amount of soil moved by (primary, secondary or tertiary) tillage is as important (or more important) than remaining residue cover left on the soil surface;
2. Tillage erosion is the primary threat to soil productivity, not wind and water erosion;

3. Soil conservation efforts may reduce soil losses, but they will not necessarily restore soil health and productivity (to do so requires extraordinary efforts…e.g. increasing crop biomass production; importing crop biomass; soil-landscape restoration)
4. Integrated assessment of soil erosion is essential, combining wind, water and tillage erosion, and their interactions.

These recommendations are incorporated into the following implementation plans and future research suggestions.

5.4.1. Identifying areas to benefit from soil landscape restoration implementation

5.4.1.1 Starting with the correct perspective

Similar to the beginnings of the adoption of no-till on the Canadian Prairies in the 1980s and 1990s (Henry, 2024), it quickly became apparent that the simple removal of tillage from current production systems at that time would not be sufficient for success, due to the issues with weed control, excess moisture restricting timely operations, crop residue management and limitations of available seeding equipment at the time. It would require a whole-systems approach that considered and addressed several factors to allow no-till production systems to succeed in the long term. Likewise, for soil landscape restoration, it will not likely be sufficient to simply add topsoil from one part of a field to another and expect real, consistent, long-term crop productivity improvements to occur immediately and without other adjustments to the current production system. Factors such as constructing a restoration plan based on field characteristics and investigations, establishing target bulk densities on areas receiving added topsoil, increasing seeding rates, adjusting fertilizer strategies, redistributing crop residues and implementing tillage (or no-till) strategies will all need to be considered and used in conjunction with landscape restoration to ensure maximum success for the long-term.

5.4.1.2 Potential area to benefit from soil landscape restoration

The percentage of cropland in the Canadian Prairies in high and very high tillage erosion risk classes has been steadily decreasing, from 13% in 1981 to 3% in 2021. (https://agriculture.canada.ca/en/environment/resource-management/indicators/soil-erosion-risk-indicator). However, the distinction must be made between the *risk of further erosion* by tillage and the current productive state of *eroded* soils that have been stabilized by conservation tillage and other BMPs. Although the area has been decreasing, the cumulative severity of the degradation continues to worsen. Since soil-building is an extremely slow process and is needed to reverse the downward-spiral effects of low yields and low crop biomass productivity feeding into low carbon soils, identifying portions of agricultural landscapes that would benefit from soil landscape restoration is a key practice.

From the above report, Lobb et al. (2024) calculated the percentage of cropland by province in the various tillage erosion risk classes from select years from 1981 to 2016. In 1981, the percentage of cropland in the "moderate" to "very high" risk classes (i.e. from 11 to >33 t ha^{-1} yr^{-1}) was 13.1% for Alberta, 26.6% for Saskatchewan and 9.5% for Manitoba. That converts to approximately 1.3 million ha in Alberta, 4 million ha in Saskatchewan and 423 000 ha in Manitoba that may have been impacted by the negative, cumulative effects of tillage erosion since 1981. Locating these areas may be challenging as they will tend to exist as discrete landforms within a field parcel and not the entire land parcel.

Specifically, for Manitoba there are approximately 775,000 ha of soils with CLI agriculture capability subclass limitations of T (topography), E (erosion), or M (lack of moisture) (Manitoba Agriculture, 2006). A conservative estimate of 10% of these areas are uplands that would warrant assessment for soil landscape restoration, or approximately 77,500 ha for more detailed inspections.

Other clues or features to search in the identification phase:

1. Undulating, hummocky or rolling terrain
2. Use of remote sensing to identify and quantify the lack of darker-colored topsoil on hilltops (i.e. the presence of white or light-colored knolls)
3. Use of Lidar or elevation data to identify steep slopes, 9% or higher, especially with convex curvature
4. Yield maps with less than 50% of the long-term yield potential compared to that in mid- to lower-slope positions (regardless of the current tillage or cropping system)

5.4.1.3. Developing a practical soil landscape restoration plan

As attempts are made to expand the awareness, implementation and adoption of soil landscape restoration practices among agronomists, producers and landowners, some adjustments will be needed for investigations made for research-intensive trials that may not be timely, cost-effective or practical for commercial field-scale activities, such as:

1. Collect background information: for each candidate land parcel identified (assuming a quarter section parcel or subset if in Western Canada), obtain the following: current and historical map/aerial photo of site; detailed soil survey report (< 1:50 000 if available); recent yield maps (if available); topographic data (elevation, slope, slope curvature data), with a minimum of four general landforms and their proportional areas of the field identified. An on-site visit is always preferred to confirm landscape and soil properties.
2. Identify knolls to receive topsoil (target areas) and corresponding depressions from which to remove topsoil (source areas) with minimal negative effects (check for salinity, stones,

depth of topsoil, risk of excess water ponding, textural changes with depth and textural differences from source and destination). For target areas, the current depth of the A horizon is greater than 25 cm and the depth of topsoil removed by erosion was less than 5 cm (Zhang et al., 2021). Determining depth of lost topsoil can be difficult, having to rely on either historical soil survey records or use of radionuclide tracers such as ^{137}Cs to determine erosion rates (Lobb et al., 1995). For depressions, avoid all source areas that are saline, stony, and those with less than twice the topsoil depth that is planned to be removed (i.e. if removing 15 cm of topsoil, the source area should have at least 30 cm of topsoil prior to removal), etc.

3. Conduct individual soil sampling on each of the source and target areas to confirm the above properties; ideally, conduct ^{137}Cs analysis for tracer assessment and to assess severity of erosion/deposition. It may be necessary to scale up ^{137}Cs analysis for erosion assessments for timely, cost-effective, producer-based service, or recommending an acceptable proxy measurement, such as mapping the depth of topsoil using non-destructive sensor technology. Recommended strategies for background soil sampling (for nutrients, salts, carbon, moisture, bulk density, plus historical yield maps, terrain data, etc) are required as an initial starting point (Table 5.4) to track changes over time.

Table 5. 4. Relative ranking of various erosion assessment criteria.

Property	Utility for erosion assessment
Yield maps	High (knolls $\leq$50% of depressions, with goal $\geq$80%
^{137}Cs	High (erosion status $\geq$ 20 Mg ha^{-1} yr^{-1})
Organic Carbon	High (especially if stocks concentrated near surface of soil profile)
Inorganic Carbon	High (especially if stocks concentrated near surface of soil profile)
EC	High - to ensure salts are not moved uphill
Soil Survey information	Depends; historical?
Depth of topsoil	Knoll: $\leq$10 cm unmixed topsoil; Depression: $\geq$30 cm topsoil available
Bulk Density	Useful for conversion of concentrations to stocks/inventories; AWHC
Water-Stable Aggregates	Limited; more data points over time
Soil moisture	0-30 cm depth NB; most likely a positive response if AWHC in depression >> AWHC in knoll

Soil nutrient status (N, P)	Unclear on its own – interpretation required for nutrient fate based on landscape position and past management practices
K_{sat}	No - unless many more samples are taken (time commitment?)
pH	?

4. Design a landscape restoration plan to re-distribute topsoil (depth removed vs depth to add) with minimal in-field equipment travel, disturbance, compaction, surface drainage effects, etc. Take soil samples to depths of at least 20 cm and analyze for SOC concentrations and AWHC as a preliminary assessment of site suitability for soil landscape restoration.
5. Execute the landscape restoration plan with the appropriate size of equipment (ideally in fall after harvest) when soils are reasonably dry to minimize soil compaction.
6. A checklist is needed to track changes in soil properties and crop performance between the knolls and depressions, as well as restored and unrestored areas of the corresponding landscape positions. Items would include but are not limited to: plant counts, time to emergence, soil cover, soil temperature at 5 cm depth, soil moisture at standardized depths, crop biomass and grain yield. In addition, key weather data, such as growing degree days and precipitation events, and their corresponding monthly % of normal values, are extremely valuable in determining the long-term frequency and degree of response to landscape restoration and their associated practices. Track performance over time with subsequent yield maps, soil testing, crop sampling from treated/untreated source and target areas.
7. To encourage adoption and continuous learning about soil landscape restoration as a BMP, evaluation by groups of farmers, agronomic and economic advisors under the Yield Enhancement Network (YEN) framework, currently being set up in Ontario and Manitoba, as a potential technology transfer vehicle (https://greatlakesyen.com/); (https://www.youtube.com/watch?v=IvStI1a-Dtk&list=PLaNpczapd8GE6heQ-gLGAyuivfIm5No-9&index=15).

Using the above activities, it would be a reasonable goal to double producer adoption rates in Canada from 6% (Statistics Canada, 2019) to 12%, over the next 3-5 years, but this is only important if it can be demonstrated that soil landscape restoration consistently increases productivity gains over a range of soil types, crops grown and variable weather conditions.

5.5. Future research to enhance current knowledge

5.5.1. How to utilize tillage as a management tool, post-soil landscape restoration

Conceptually, low-disturbance, no-till production systems offer the best chance for tillage erosion processes to cease under annual crop production. However, producers need to be mindful of tillage erosion that can be caused by secondary tillage operations to manage crop residues (i.e., harrows) or other occasional tillage that has been recommended as low-disturbance but can be highly erosive because of high travel speeds. This includes many, if not all, of the vertical tillage equipment currently being offered in the marketplace. More work is needed on evaluating the erosive nature of various tillage equipment, based on equipment design, recommended travel speed, horsepower requirements and fuel consumption.

If tillage operations must be used post-soil landscape restoration, then a new, strategic approach is needed to avoid further significant tillage erosion. Based on the intended purpose of tillage (seedbed preparation, weed control, residue management, etc.) and the type of tillage implement to be used, it may be possible to use tillage in a more sustainable manner that does not compromise the benefits of soil landscape restoration. Frequency, speed and direction of tillage need to be high priority when utilizing tillage in a post-restored landscape, which may be highly possible with the use of autonomous equipment and prescribed travel pathways across a field parcel, developed with the primary purpose of minimizing the movement of soil downslope. Strategic tillage, coupled with more intense and diverse crop rotations, which include the use of cover crops, may produce outcomes similar to those expected with low-disturbance, no-till systems.

5.5.2. Weed management in variable landscapes

Although not discussed directly, the effect of weed management on crop responses was a major consideration throughout this study. Of particular importance is the relationship between non-chemical weed control at the expense of soil health because of increased tillage (and thus tillage erosion) to manage herbicide-resistant weeds. The influence of landscape position on weed populations and species was evident at the Altamont site where weed counts were high. The effect of soil landscape restoration on soil properties such as soil moisture, organic carbon and their implications on weed growth, crop competition and herbicide efficacy are important considerations for additional research in weed and landscape ecology. Of particular interest is the potential effect of crop residue redistribution on weed management and soil health properties should be examined to determine, similar to moving topsoil uphill, whether there is an overall additive effect in removing residues from depression areas with excess moisture limitations and transferring them to knolls where erosion, runoff and lack of moisture are the main limitations. Redistribution of crop residues (especially chaff rather than straw, but includes both) at least semi-annually, in a similar fashion as was done with topsoil in soil landscape restoration, may be another BMP that has potential to reduce evaporation, stifle weed growth and sustain soil moisture as long as possible between precipitation events. This is a practice that has existed for some time but currently has low producer adoption rates in Canada. Further investigations are required to determine application rates that provide the above benefits without impeding seeding operations, crop establishment or immobilization of nutrients.

5.5.3. Economics of soil landscape restoration

Previous economic analyses by Bosma (2004) and Hacault (2011) provided estimates of the payback period of soil landscape restoration. It is assumed that production systems employed post-restoration will either be no-till or highly strategic-till, as outlined in a previous sub-section, to maximize the longevity of the effects from soil landscape restoration. The conundrum is that eroded hilltops and in general, fields with high variability, require the most effort and expense to be managed effectively, but by their nature are least likely to deliver a positive response over time, which has stifled much of the interest in addressing this issue to date. The good news is that the most severely-affected sites tend to be the most responsive to restoration activities; furthermore, the benefits of having a once highly-variable landscape behave more uniformly from soil landscape restoration could be monetized in a number of ways, not the least of which would be less reliance on variable rate technology on seeding equipment.

If costs such as equipment, labour and time are sourced in-house from farm operations rather than out-sourced as a custom rental charge, then costs of soil landscape restoration will be much more subtle and incremental in nature, but may take more time to complete. Beyond potential increases in crop yields, increases in crop biomass, soil moisture and soil organic carbon/organic matter are much more intangible and difficult to assign an economic value that can be recognized in the short- to medium-term.

5.5.4. Agrometeorological data

Predicting the frequency and magnitude of positive crop responses from soil landscape restoration are expected to be highly weather-dependent. More site-years of data, coupled with a range of soil, weather and management conditions, would greatly aid in determining a range of scenarios in which crop responses on restored knolls is most likely, decreasing as conditions move away from normal/optimum and towards more extreme dry and extreme wet growing conditions. As conditions become more extreme, additional moisture management practices would be required to ensure a positive outcome that would likely not be realized using soil landscape restoration on its own.

Providing the tools and expertise needed to measure various soil landscape factors to the most interested and committed producers, landowners and agronomists is crucial for the collection of sufficiently-sized data sets to model, test and implement solutions that enhance our collective learning on the subject. Table 5.5 is a summary of the suggested future steps in enhanced management of variable and complex agricultural landscapes.

Table 5. 5. Summary of suggested next steps in landscape management.

Research	Development	Technology Transfer
Answer the "Why"	**Answer the "What"**	**Answer the "How"**
Effective collaborations among soil scientists, agronomists, engineers, economists, etc.	*Putting landscape management principles and technologies in the hands of producers and other non-researchers*	*Assist producers in becoming more efficient, profitable and environmentally-responsible*
Soil landscape restoration – Phase 2 (more sites, crops, soil types)	Scaling up activities with soil landscape restoration plans	Setting and adjusting priorities by landscape, soil type, crop rotation and growing season
Crop residue redistribution: influences on soil moisture, temperature, weed growth and nutrient mineralization	Commercialization of wind, water and tillage erosion assessments and moisture measurements and fates	Stacking other BMPs on top of soil landscape restoration (including livestock integration) via "Yield Enhancement Network" style activities
Strategic tillage to combat tillage erosion and manage herbicide-resistant weeds	Assessing tillage equipment performance based on soil erosivity, horsepower needs and other soil health factors	Developing tillage travel pathways, field prescriptions

5.5.5. Performance measures of soil landscape restoration for consideration

i. Number of producers practicing soil landscape restoration, by province;

ii. Number of acres put into landscape restoration (distinguish between entire land parcels such as quarter sections and the number of affected acres, i.e. topsoil removed and topsoil added, by this practice);

iii. Changes in relative yield (i.e. leave at least one "control" area of unaffected topsoil redistribution) over time, by crop, by weather conditions;

iv. Other landscape "drivers" such as infiltration, runoff, water storage, fertility, carbon, crop biomass, etc that could enhance our understanding of landscape dynamics for the future;

v. Operational changes experienced by the producer from landscape restoration (potential indirect, "soft" changes, such as more field uniformity, weed dynamics, less extremes in water distribution, increased windows for timely operations, etc. These may be difficult to measure and could be anecdotal in nature, but may prove to be important for continued improvement to and the adoption of landscape restoration as a sustainable management and increased productivity practice.

5.6. Final thoughts

The author is grateful for the opportunity to work with many individuals across disciplines, generations, geographic locations, perspectives, etc. to find truth and opportunities to address one of the oldest known global problems and attempt to make things better, now and for the future, with the farmer as the key steward (and beneficiary) at the forefront. If nothing else, this has been a tremendous bridge-building activity.

5.7. References

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Appendices

Table A1. *P* values for statistical analyses.

Source	Constituent	Depth (cm)	Normality (W stat)	Position effect	Site effect	Treatment effect	Interaction (specify)	
Fig 2.9	^{137}Cs inventories		0.991		0.6141	<0.0001	Site × Trt	0.8422
Fig 2.10	SOC concentration	0-5	0.901		<0.0001	<0.0001	Site × Trt	0.0069
		5-15	0.994		<0.0001	<0.0001	Site × Trt	0.0062
		15-30	0.970		<0.0001	<0.0001	Site × Trt	0.3201
		30-60	0.958		0.0004	0.0047	Site × Trt	0.0050
		60-90	0.975		<0.0001	0.0422	Site × Trt	<0.0001
	IC concentration	0-5	0.717		0.8748	0.0067	Site × Trt	0.0110
		5-15	0.960		0.0019	<0.0001	Site × Trt	<0.0001
		15-30	0.983		0.0132	0.0062	Site × Trt	<0.0001
		30-60	0.872		<0.0001	0.0079	Site × Trt	<0.0001
		60-90	0.902		<0.0001	0.0657	Site × Trt	<0.0001
Fig 2.11	SOC stocks (inventories)	n/a	0.943		0.0370	<0.0001	Site × Trt	<0.0001
Table 2.6	Bulk Density	0-5	0.963		0.0690	0.0012	Site × Trt	0.0423
		5-15	0.991		<0.0001	0.8100	Site × Trt	0.0240
		15-30	0.985		<0.0001	0.3425	Site × Trt	0.0002
		30-60	0.826		<0.0001	0.4723	Site × Trt	0.0471
		60-90	0.897		0.0231	0.1477	Site × Trt	0.1353
Table 2.7	Water-Stable Aggregates	n/a	0.985		0.0003	<0.0001	Site × Trt	0.3486
Table 2.8	K_{sat}	n/a	0.887		0.2776	0.5433	Site × Trt	0.2968
Fig 2.12	pH	0-5	0.987		0.0003	0.2341	Site × Trt	<0.0001
		5-15	0.975		<0.0001	0.0008	Site × Trt	<0.0001
		15-30	0.973		<0.0001	<0.0001	Site × Trt	<0.0001
		30-60	0.987		<0.0001	0.3351	Site × Trt	0.0009
		60-90	0.927		0.0035	0.0250	Site × Trt	<0.0001
Fig 2.13	EC	0-5						
		5-15						
		15-30						
		30-60						
		60-90						
Table 3.3	Crop Biomass	n/a					Site × Trt × Year	0.0001
Table 3.4	Crop Yield	n/a					Site × Trt × Year	0.0001

Source	Constituent	Depth (cm)	Normality (W stat)	Position effect	Site effect	Treatment effect	Interaction (specify)	
	Soil Moisture	0-5	0.983			<0.0001		
		5-15	0.989			<0.0001		
		15-30	0.997			<0.0001		
		30-60	0.986			<0.0001		
		60-90	0.969			0.0001		
Fig 3.14	Fall NO3-N concentrations	0-5	0.990		<0.0001	0.0020	Site × Trt	0.0093
		5-15	0.989		<0.0001	<0.0001	Site × Trt	0.1698
		15-30	0.980		<0.0001	<0.0001	Site × Trt	0.5484
		30-60	0.982		<0.0001	0.0017	Site × Trt	0.2746
		60-90	0.949		<0.0001	0.0360	Site × Trt	0.0385
Fig 3.15	Fall Olsen P (PO4-P) concentrations	0-5	0.931		0.1206	0.1339	Site × Trt	0.0013
		5-15	0.981		0.0031	<0.0001	Site × Trt	<0.0001
		15-30	0.988		<0.0001	<0.0001	Site × Trt	<0.0001
		30-60	0.989		<0.0001	<0.0001	Site × Trt	<0.0001
		60-90	0.989		<0.0001	0.0003	Site × Trt	<0.0001
	Fall NH4-N stocks		0.974			0.6282		
	Fall NO3-N stocks		0.977			<0.0001		
	Fall PO4-P stocks		0.988			<0.0001		
Fig 4.2	Crop Biomass (wheat)			<0.0001				
	Crop Biomass (flax)						Site × Trt × Position	0.0016
	Crop Biomass (barley)							
Fig 4.3	Crop Yield (wheat)						Trt × Position	0.02
	Crop Yield (flax)						Trt × Position	0.01
	Crop Yield (barley)						Trt × Position	0.02

Table B1. Summary of crop yield increases from the addition of topsoil in previous soil landscape restoration research.

Research	Year	Site	Topsoil Added (cm)	Years after restoration	Crop	% Yield Increase (actual change in kg ha^{-1})	Yield Increase (bu ac^{-1})	Yield Decrease (bu ac^{-1})	Relative Weather Cond's
Schneider et al. (2021)	2006-2011	MN	15-20	1 - 6	Corn Soybean	20-49% 12-59%	30 - 46 4 - 13	13-40 7-19	Dry
Liang et al. (2018)	1997	OH	20	15	Corn	47% 7.45 Mg ha^{-1}			
Smith (2008)	2005	Treherne MB	10	1	Barley	31% From 1810 to 2365	10 From 34 to 44		Wet
	2006	Treherne MB	10	2	Pea	64% From 1249 to 2049	13 From 20 to 33	11 NS	Dry
	2005	Brookdale MB	20	2	Oat	10% From 2831 to 3121	8 From 79 to 87		Wet
	2006	Brookdale MB	20	3	Flax	40% From 1907 to 2679	13 From 30 to 43		Dry
	2006	Bruxelles MB	10	1	Wheat	133% From 796 to 1856	16 From 12 to 28	NS	Dry
	2006	Swan Lake MB	10	1	Flax	94% From 404 to 784	6 From 6 to 12	6 From 32 to 26	Dry
Erb (2005)	2003	Brookdale MB	10	<1	Flax	18% From 1195 to 1407	3 From 19 to 22		Dry
					Pea	67% From 1833 to 3061	20 From 29 to 49		Dry
Larney et al. (2009)	1990-2006	Lethbridge AB	5	1-16	Wheat (dryland)	20% From 1900 to 2280	6 From 28 to 34		31-183% of normal
					Wheat (irrigated)	14% From 2880 to 3280	6 From 43 to 49		Dryland + 100 to 200 mm
Verity and Anderson (1990)	1986	SK	5-15	1	Wheat	45-58% From 914 to 1443	7 From 14 to 21		Drier
	1987	SK	5-15	2	Wheat	42-88% From 1143 to 2150	15 From 17 to 32		Wetter

Table B2. Crop Yields (bu ac^{-1}) by site and treatment.

Site Year	Crop	Control Depression (CD)	Removed Depression (RD)	% Change	Control Knoll (CK)	Added Knoll (AK)	% Change	CK÷CD %	AK÷RD %
				Altamont					
2021	Wheat	54	35	- 35*	13	12	-8	24	34
2022	Canola	11	1	-90*	28	34	+21*	255	340
2023	Wheat	22	19	-14	13	15	+15	59	79
2024	Canola	20	5	-75*	21	22	+5	105	440
				Bruxelles					
2021	Wheat	55	39	-29*	24	17	-29	44	44
2022	Oat	116	102	-12	64	96	+50*	55	94
2023	Canola	36	35	-3	19	28	+47*	53	80
2024	Wheat	83	70	-16	40	63	+58*	48	90
				Manitou					
2021	Canola	20	26	+30	0.7	0.7	0	0	0
2022	Soybean	59	58	-2	14	17	+21	24	29
2023	Wheat	49	44	-10	15	18	+20	31	41
2024	Canola	45	42	-7	35	33	-6	78	79

(* = significant at $\alpha = 0.05$)

Table B3. Weighted average yields (bu ac^{-1}) for MASC Risk Area 5, 2024 (all sites).

Crop	Weighted Average Yield	Risk Area 5 Acres (2024)
Canola	40	283 184
Oat	138	46 454
Soybean	50	115 688
Wheat	73	278 927
Corn	145	46 424
Barley	86	33 590
Dry Bean	2318 lb ac^{-1}	31 348
Field Pea	66	19 906
Flax	36	5 282
Sunflower	2010 lb ac^{-1}	3 812

Table B4. Sufficiency ranges (%) for macronutrients by crop (stage) – (Agvise Laboratories, 2024).

Nutrient	Grain (flag leaf)	Canola (bolting)
N	3.8 – 5.0	2.0 – 4.5
P	0.3 – 0.5	0.28 – 0.69
K	2.0 – 3.5	2.9 – 5.1
S	0.20 – 0.50	0.17 – 1.04

Table C1. Watering Schedule (Phases 1-3) and Precipitation Events for Phase 4.

Experimental Phase (Crop)	Year	Julian Date	Water Added (L)	Water Added (mm)	Crop Stage	Notes
1 (wheat)	2023	65	1.0	31	Planting	Fertilizer added
		69			First emergence	
		72	0.25	8		
		74			Second leaf	
		76	0.25	8		
		79	0.5	15	Third leaf	Fertilizer added
		83	0.25	8		
		86	0.25	8	GS 21	
		89	0.25	8	GS 21-23	
		93	0.5	15		Fertilizer added
		96	0.5	15	GS 47-51	
		97	0.315	10		
		99	0.315	10		
		103	0.315	10		
		110	0.315	10		
		114	0.315	10		
		117	0.315	10		
		121	0.315	10		
		124	0.315	10		
		128	0.315	10		
		131	0.315	10		
		135	0.315	10		
		157				Lights off
		163	Total:	226 (9.0”)		Harvest
2 (wheat)	2023	248	0.5	15	Planting	Fertilizer added
		254	0.5	15	Emergence	
		261	0.25	8		
		268	0.25	8		
		272	0.25	8		
		277	0.25	8		
		286	0.25	8		
		289	0.25	8		
		291	0.5	15		
		293	0.5	15		
		297	0.5	15		
		299	0.5	15		
		304	0.5	15		
		306	0.5	15		
		311	0.5	15		
		313	0.5	15		
		318	0.5	15		
		340	Total	213 (8.5”)		Harvest
3 (flax)	2024	10	0.5	15	Planting	Fertilizer added
		12	0.5	15		
		15	0.5	15		

		17	0.25	8		
		19	0.25	8		
		36	0.25	8		
		40	0.25	8		
		46	0.25	8		
		47	0.25	8		
		51			First bloom	
		54	0.25	8		
		59	0.25	8		
		61	0.25	8	Full bloom	
		67	0.25	8		
		73	0.25	8		
		79	0.25	8		
		88	0.25	8		
		94	0.25	8		
		128				Harvest
			Total	157 (6.3”)		
4 (barley) outdoors	2024	131			Planting	Fertilizer added
		136		18.4		
		137		0.2		
		138		0.6		
		139		22.6		
		140		6.2		
		146		74.0		
		147		0.2		
		149		0.6		
		152		0.4		
		155		11.4		
		163		7.0		
		165		3.0		
		170		28.8		
		171		7.2		
		175		14.6		
		176		0.2		
		178		10.0		
		180		0.8		
		181		16.2		
		185		8.4		
		186		0.4		
		190		0.2		
		195		0.4		
		196		28.8		
		198		12.0		
		204		7.2		
		205		1.8		
		212		0.6		
		218		4.4		
		222		7.2		
		223		11.0		

228	5.8	
229	18.2	
236	3.4	
238	0.2	
242	0.6	
243	6.6	Brought indoors
Total	339.6 mm (13.6”)	
255		Harvest

Table C2. Soil particle data by site and landscape position as determined by laser diffraction analysis.

Site	Treatment	Treatment	Location	Depth (cm)	Specific Surface Area (m^2 kg^{-1})	63-2000 µm (% sand)	2-63 µm (% silt)	<2 µm (% clay)	Textural Class
Altamont	control	D_0	depression	10	365.3	25.4	67.2	7.4	SiL
				20	373.0	19.7	73.1	7.2	SiL
				30	339.8	28.9	70.7	5.5	SiL
				40	342.3	25.4	69.0	5.7	SiL
		K_0	knoll	10	318.2	27.6	66.5	6.0	SiL
				20	305.2	24.7	70.0	5.3	SiL
				30	214.0	42.0	54.5	3.5	SiL
			sand	40	N/A	N/A	N/A	N/A	S
Bruxelles	control	D_0	depression	10	228.5	43.7	52.2	4.1	SiL
				20	266.2	34.6	60.8	4.6	SiL
				30	215.7	41.6	54.9	3.5	SiL
				40	215.2	30.3	67.4	2.3	SiL
		K_0	knoll	10	148.4	63.2	34.3	2.5	SL
				20	173.1	45.2	53.1	1.7	SiL
				30	140.1	47.3	51.8	0.9	SiL
			sand	40	3.8	100.0	0.0	0.0	S
Manitou	control	D_0	depression	10	319.1	24.2	70.5	5.2	SiL
				20	325.3	15.0	81.1	3.9	Si
				30	252.4	12.7	85.3	2.1	Si
				40	262.1	11.8	86.0	2.2	Si
		K_0	knoll	10	303.7	30.2	64.6	5.3	SiL
				20	270.0	32.4	63.3	4.4	SiL
				30	263.3	31.9	64.0	4.1	SiL
			sand	40	10.6	96.7	3.2	0.0	S

Table C3. Normalized Yield Data by Crop Phase, All Sites.

Phase	1 (Wheat)	2 (Wheat)	3 (Flax)	4 (Barley)
Treatment				
K_0	0.69	0.45	0.54	0.22
K_{10}	0.79	0.45	0.64	0.25
K_{20}	0.79	0.60	0.53	0.50
K_{30}	0.78	0.61	0.46	0.44
D_0	0.76	0.66	0.55	0.34
D_{10}	0.52	0.64	0.46	0.20
D_{20}	0.47	0.52	0.53	0.21
D_{30}	0.38	0.51	0.57	0.10
B_{60}	0.09	0.18	0.03	0.02
K_0/D_0	0.91	0.68	0.98	0.65

Table C4. ANOVA table for crop yields.

Crop (Phase)	Wheat (1 and 2)[1]	Flax (3)[2]	Barley (4)[3]
Effect	------------------------------	Yield (kg ha^{-1})	------------------------
ANOVA		*P* value	
Treatment	**.0001**	0.3486	**<.0001**
Site	**0.0025**	**0.0154**	0.7583
Site × Treatment	0.8541	**0.0178**	0.0787
Contrasts:			
K_0 vs D_0	**<.0001**	0.8040	**0.0091**
K_0 vs K_{10}	**0.0095**	0.8982	0.1516
K_0 vs K_{20}	**0.0345**	0.2545	0.1869
K_0 vs K_{30}	**0.0002**	0.8376	0.2202
K_0 vs D_{10}	0.0881	0.2545	0.6811
K_0 vs D_{20}	0.7174	0.8208	**0.0107**
K_0 vs D_{30}	0.7498	0.2295	0.0714
D_0 vs K_{10}	0.0535	0.7070	0.2484
D_0 vs K_{20}	**0.0159**	0.1667	0.1410
D_0 vs K_{30}	0.4349	0.6506	0.1156
D_0 vs D_{10}	**0.0049**	0.3711	**0.0191**
D_0 vs D_{20}	**<.0001**	0.6352	**<.0001**
D_0 vs D_{30}	**<.0001**	0.1458	**<.0001**
K_{10} vs K_{20}	0.6242	0.3109	0.8402
K_{10} vs K_{30}	0.2470	0.9386	0.7660
K_{20} vs K_{30}	0.1003	0.3487	0.9166

[1]Wheat: treatment effect (D_{20}, D_{30} sig diff from rest); site effect (Altamont = Manitou > Bruxelles)

[2]Flax: site × treatment interaction: Altamont K_{10} > (Bruxelles D_0; Bruxelles K_{30}; Bruxelles D_{10}; Manitou K_0)

[3]Barley: treatment effect: D_0 > K_0; D_0 > removed treatments; K_0 > D_{20}, D_{30}

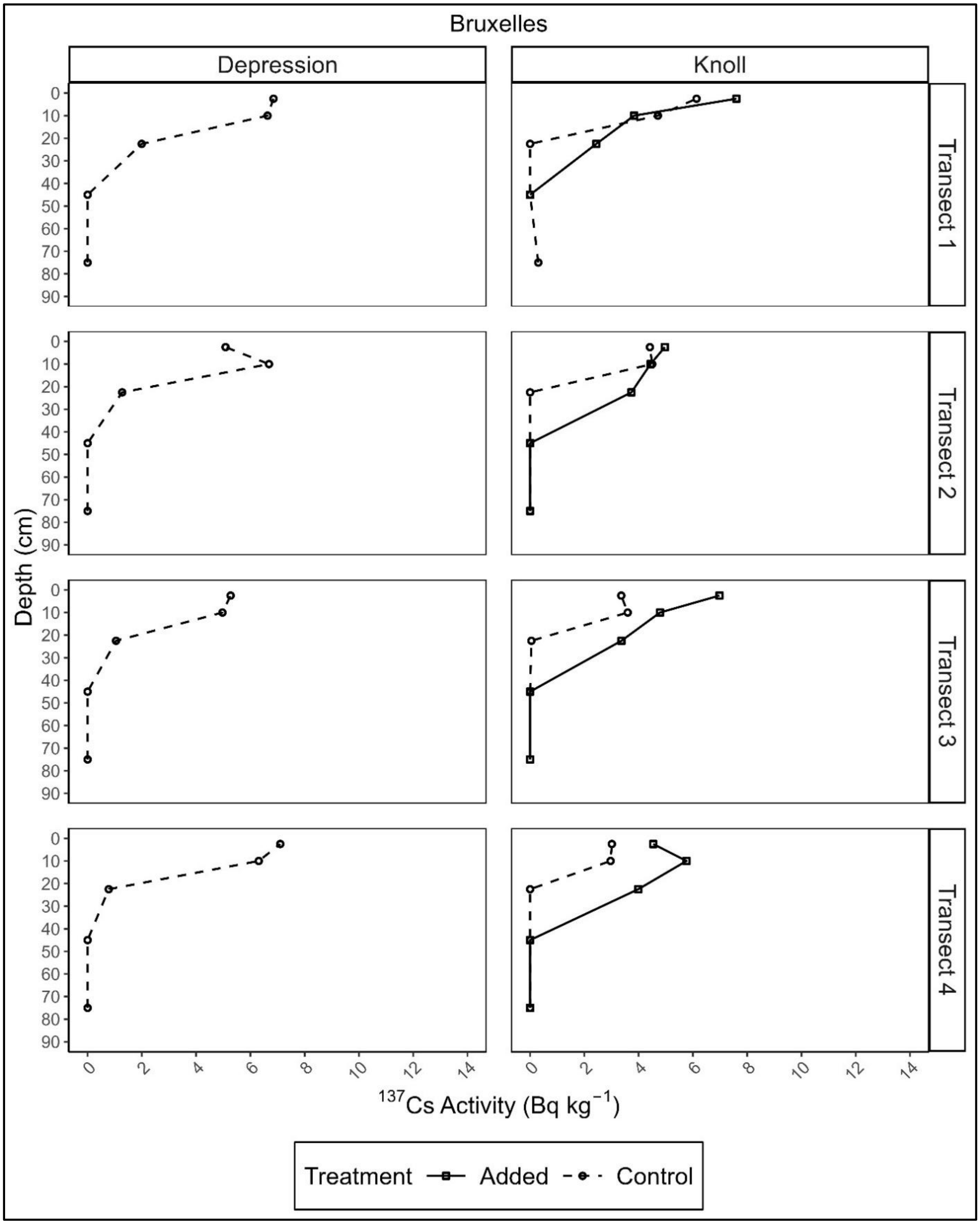

Figure A1. ^{137}Cs concentration profiles (Bq kg^{-1}) for treatments/landscape positions at Bruxelles, MB. Added refers to 20 cm topsoil added to knoll; removed refers to 20 cm topsoil removed from depression. Control is untreated conditions prior to topsoil movement for landscape restoration.

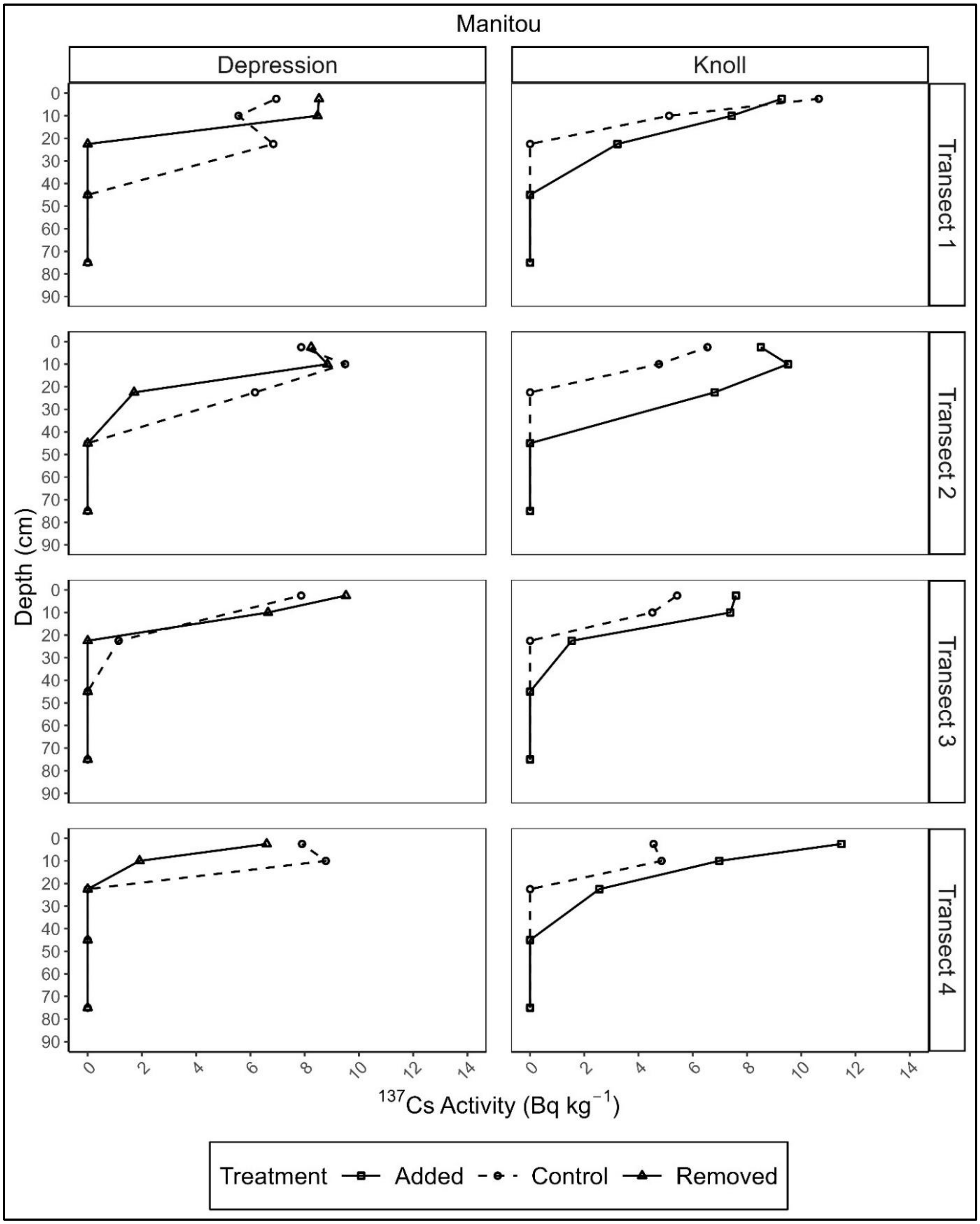

Figure A2. ^{137}Cs concentration profiles (Bq kg^{-1}) for treatments/landscape positions at Manitou, MB. Added refers to 20 cm topsoil added to knoll; removed refers to 20 cm topsoil removed from depression. Control is untreated conditions prior to topsoil movement for landscape restoration.

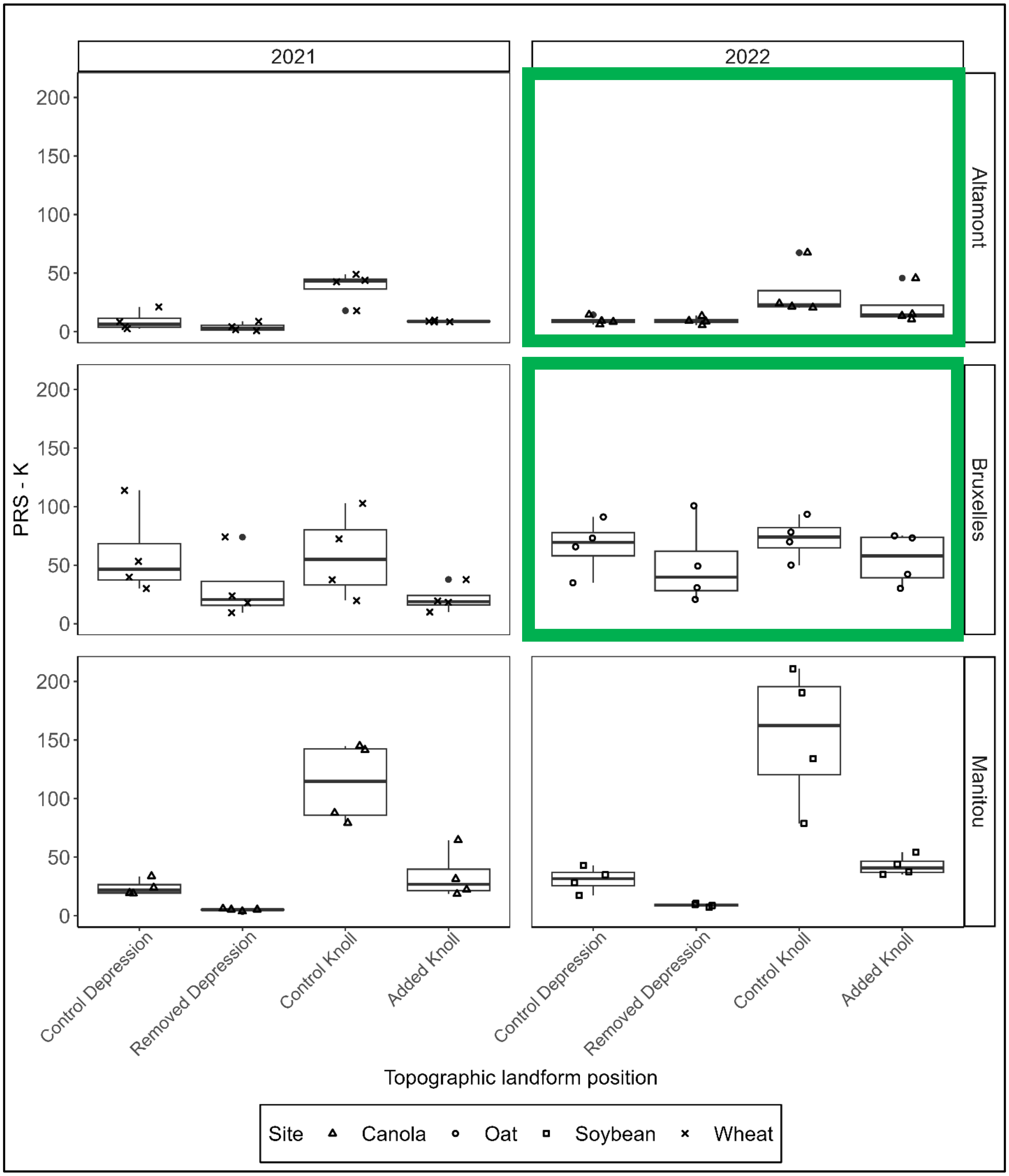

Figure B1. Plant Root Simulator® probe nutrient supply (µg 10 cm^{-2} (burial length)$^{-1}$) for potassium by crop, year, treatment and site. Site-years outlined in green were those that positively responded in crop yield to added topsoil.

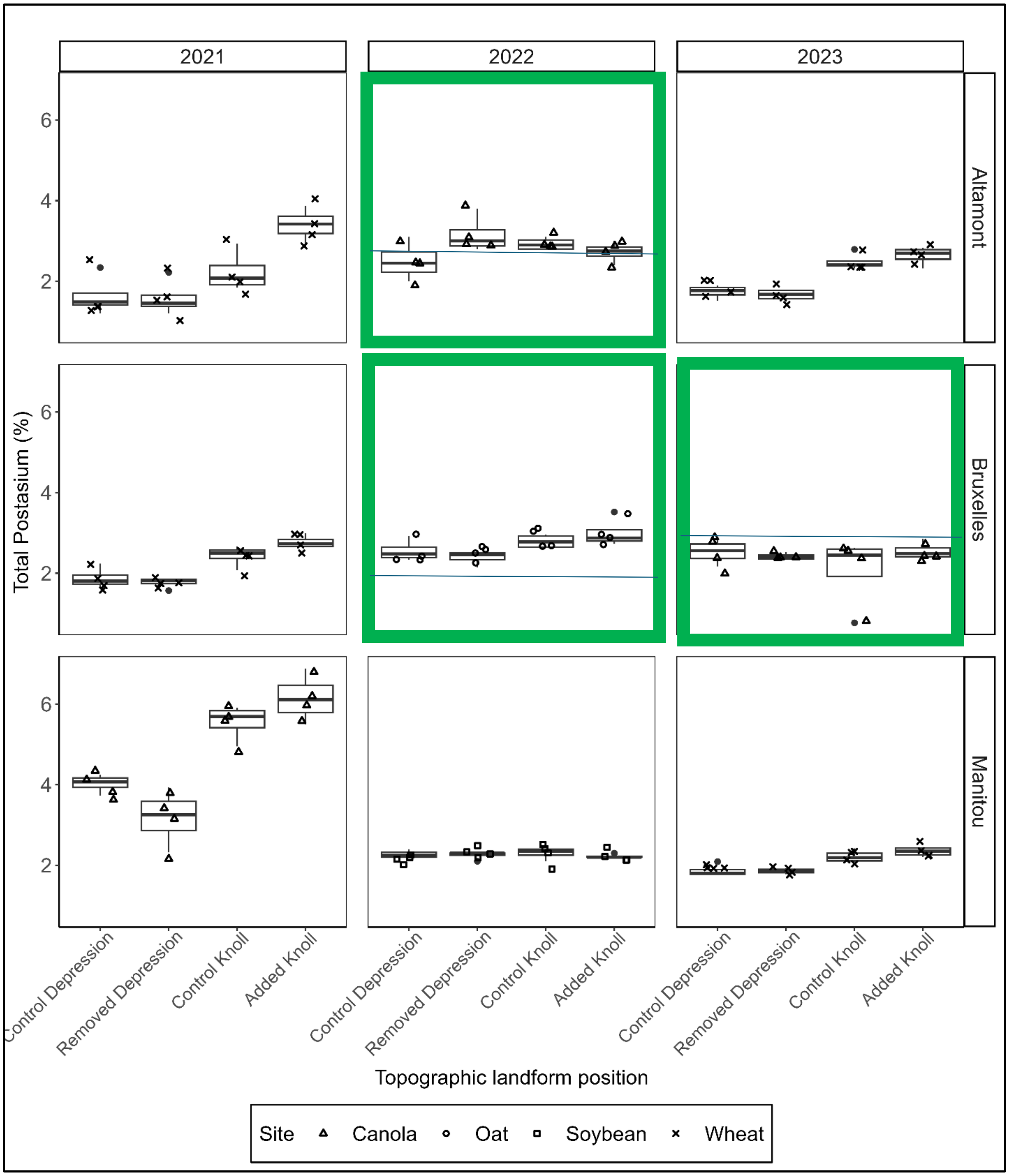

Figure B2. Plant tissue test potassium (%) by crop, year, treatment and site. Horizontal lines represent sufficiency levels for the crop in question inside the highlighted site-years in which there was a crop yield response. Site-years outlined in green were those that responded positively in crop yield to added topsoil.

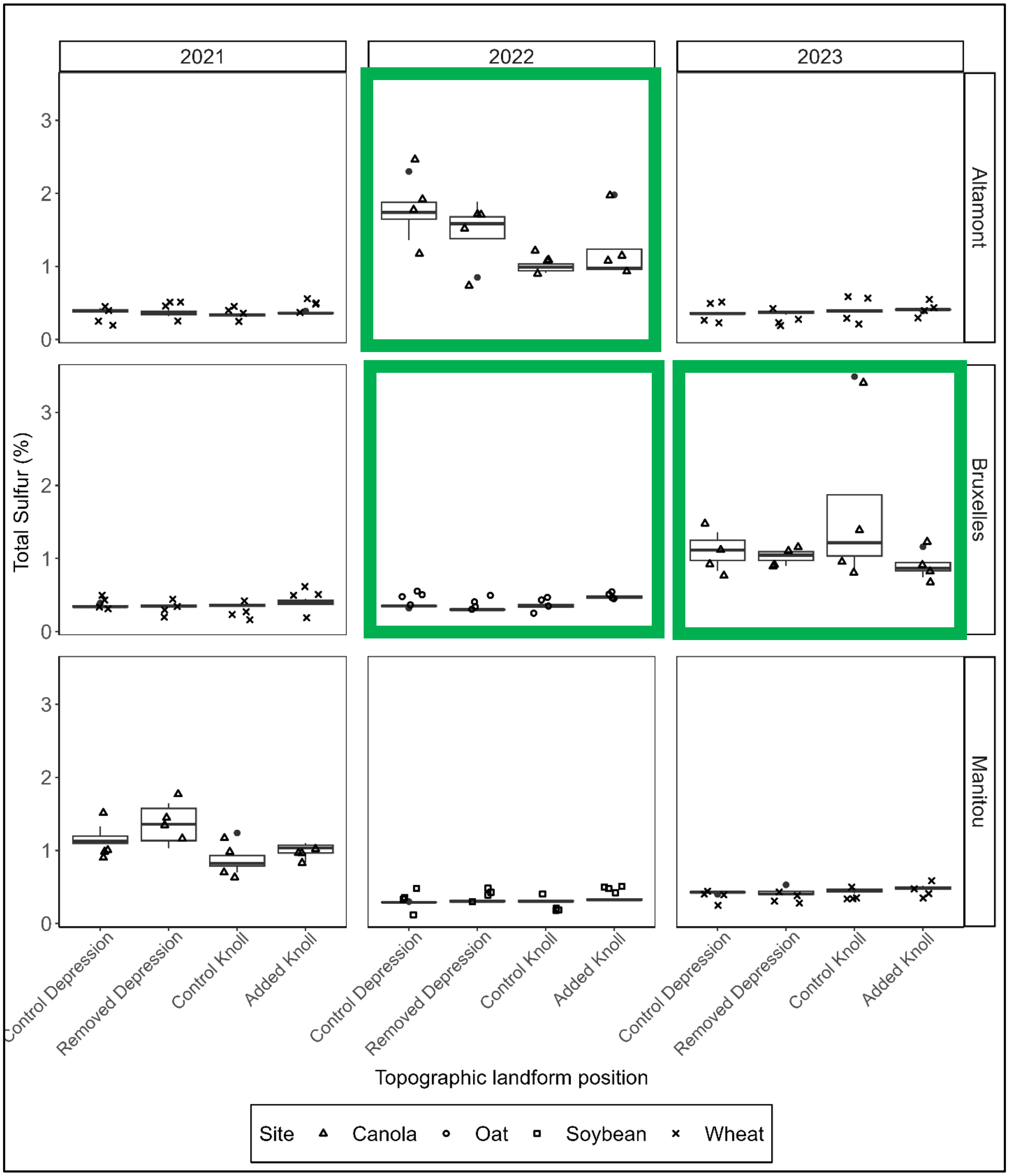

Figure B3. Plant tissue test sulfur (%) by crop, year, treatment and site. Site-years outlined in green were those that responded positively in crop yield to added topsoil.

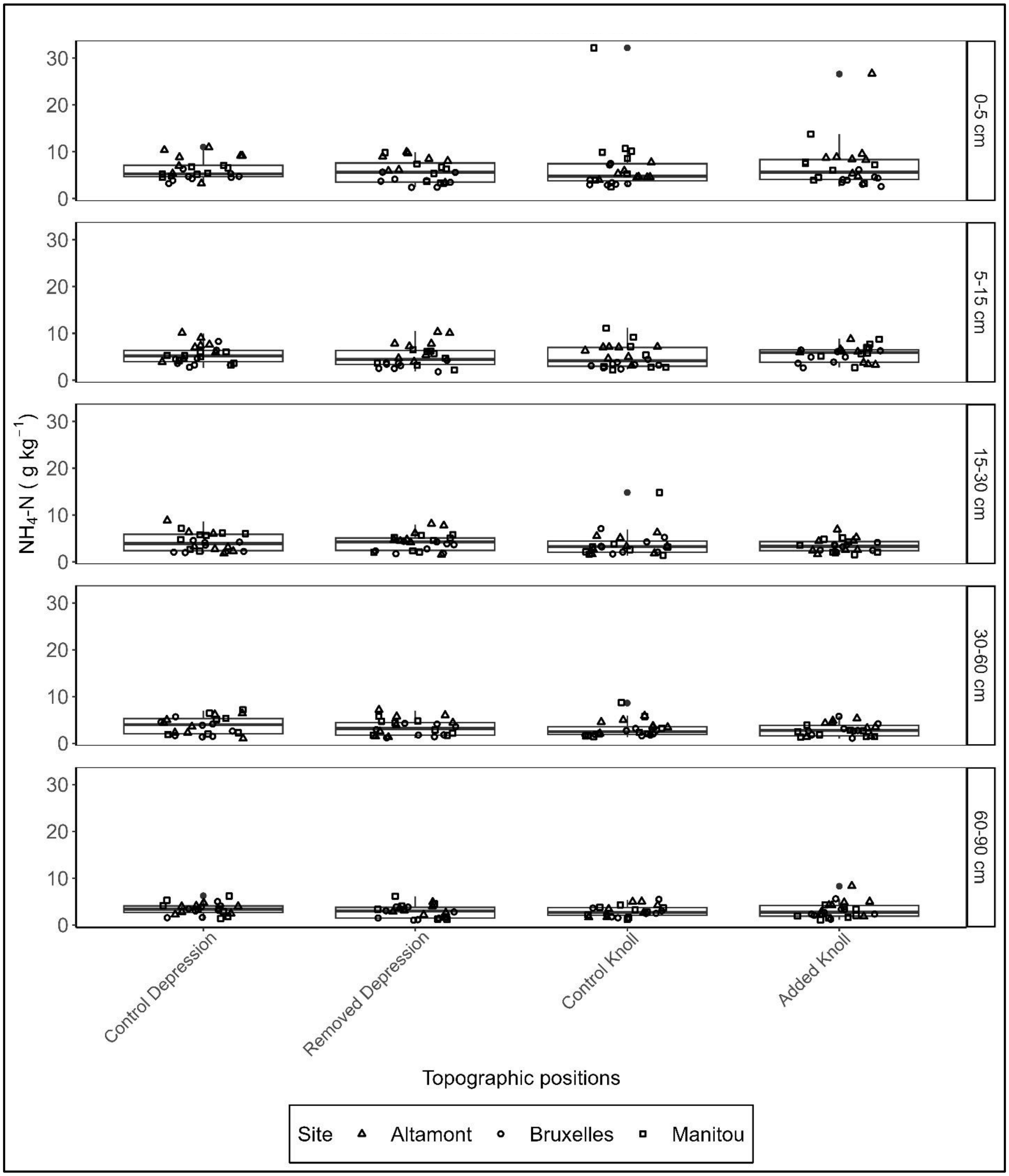

Figure B4. Fall soil test NH_4-N (g kg^{-1}), by depth, landscape position and treatment (all sites).

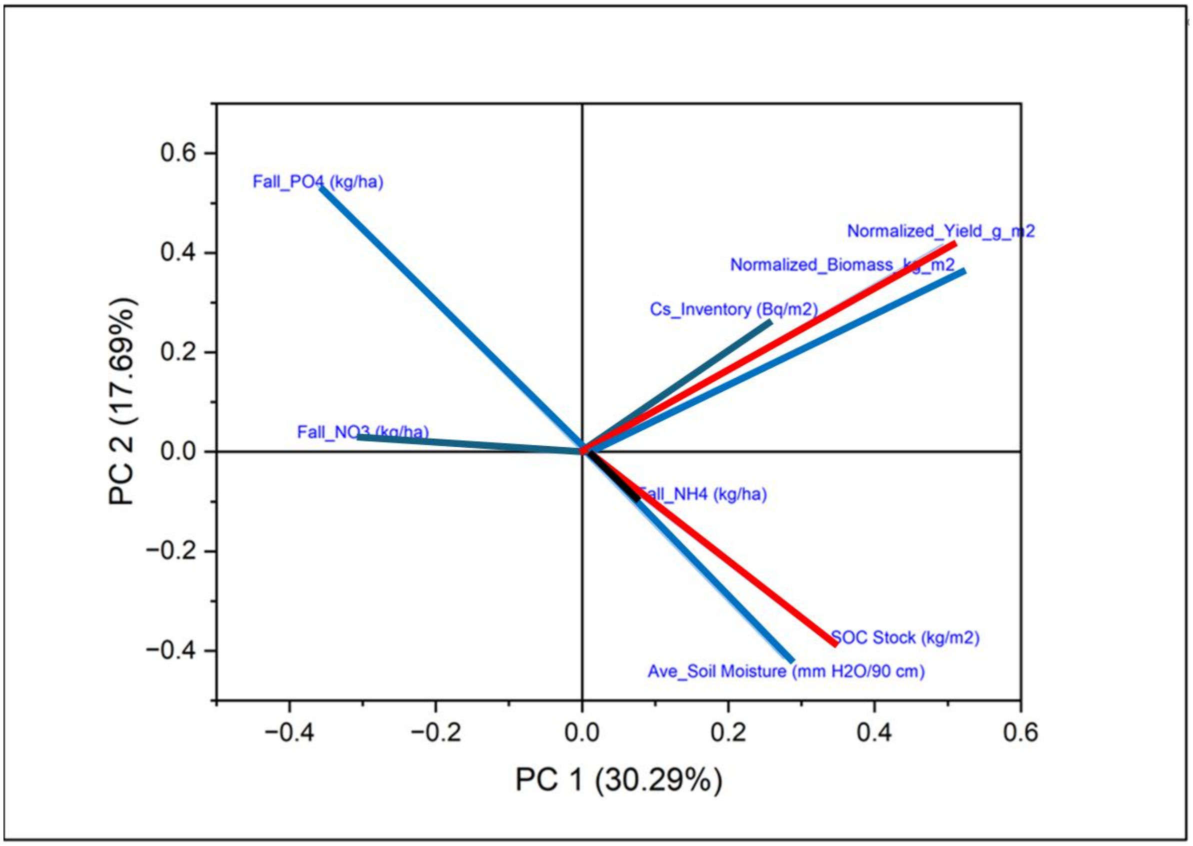

Figure B5. Two-dimensional Principal Component Analysis (all site-years).

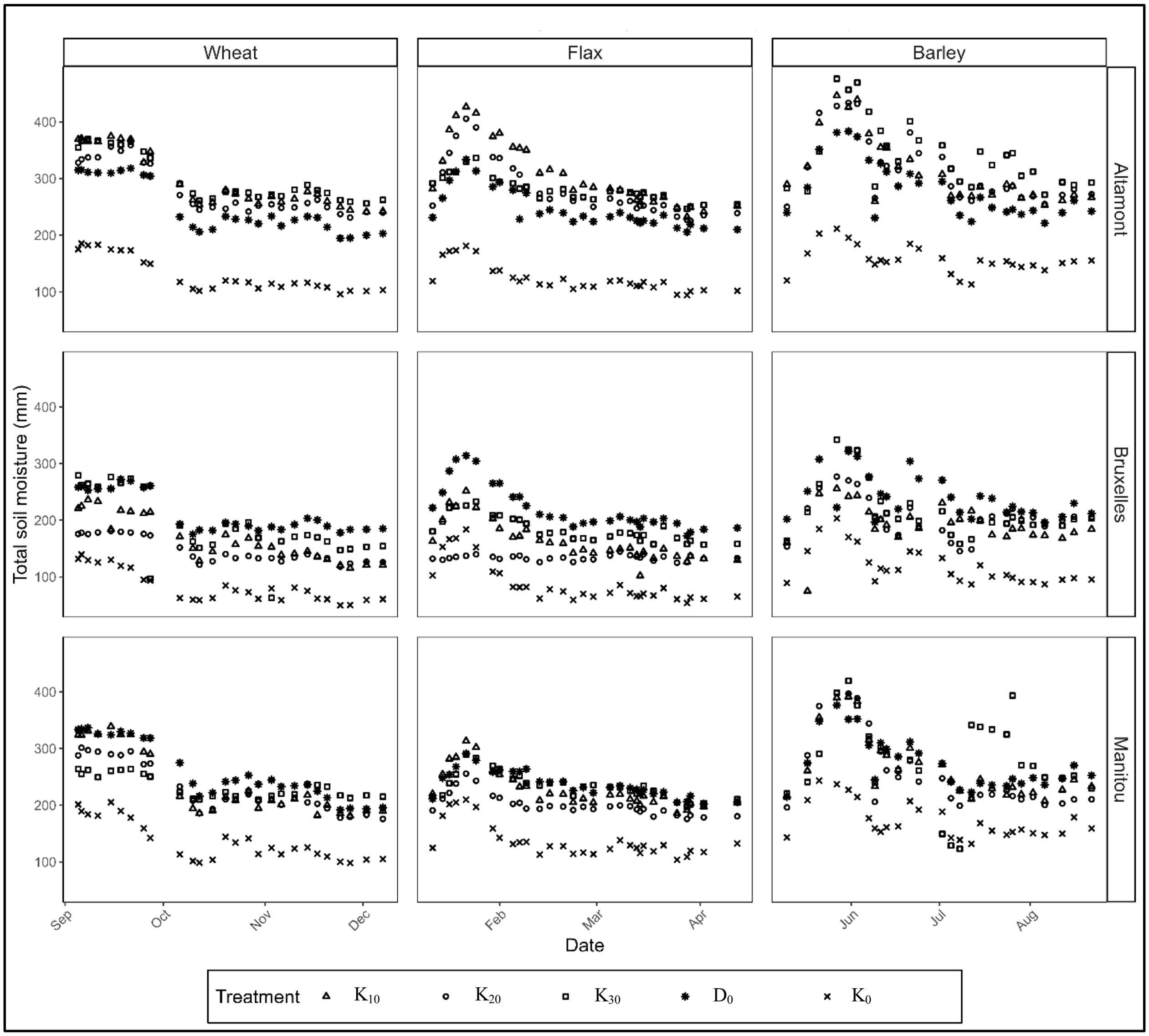

Figure C1. Changes in total soil moisture (mm) at 0-40 cm depth as affected by topsoil addition treatments, by site over wheat, flax and barley crop phases.

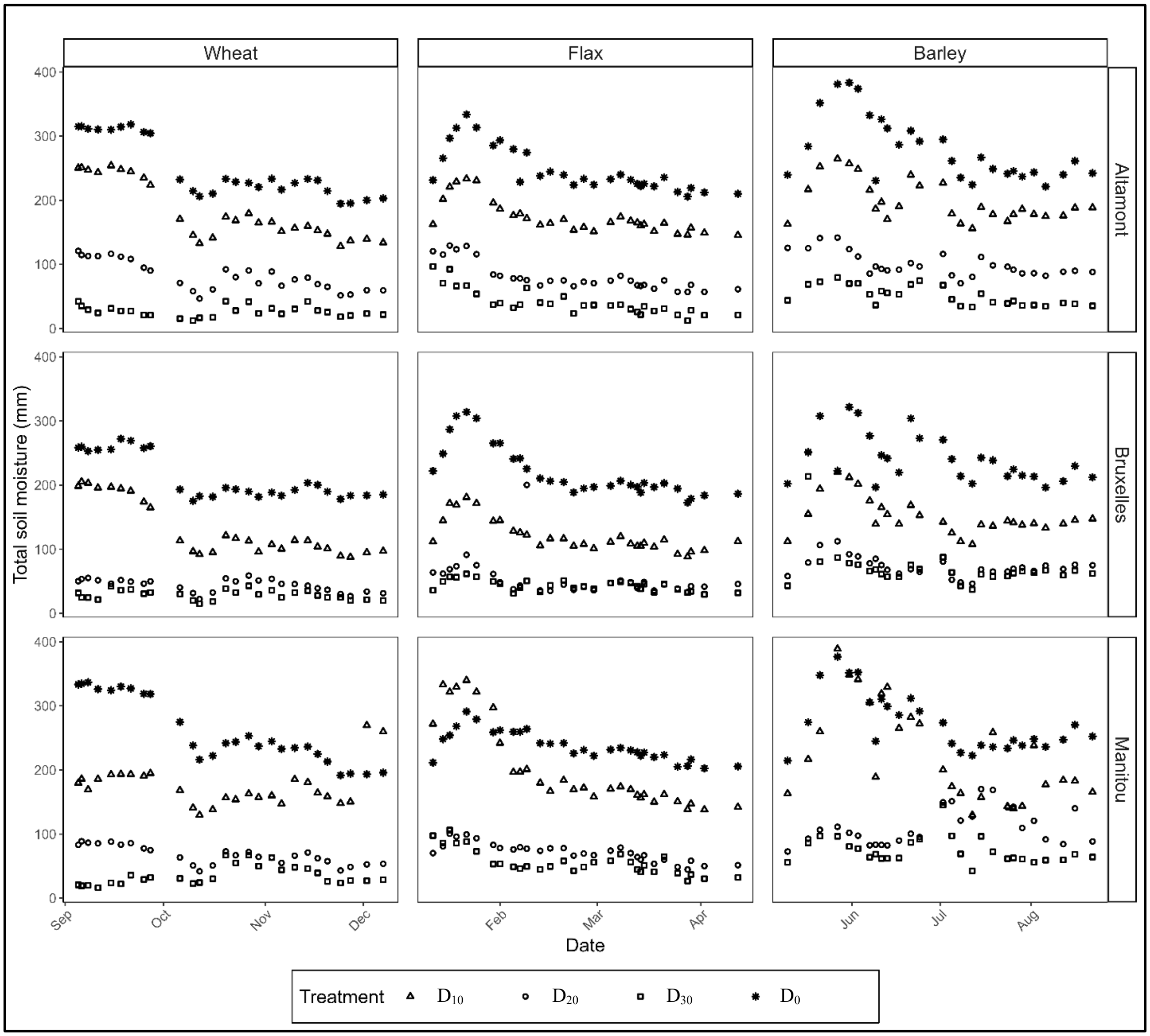

Figure C2. Changes in total soil moisture (mm) at 0-40 cm depth by site as affected by topsoil removal treatments by site over wheat, flax and barley crop runs.